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URANIUM MINERALIZATION AT THE MIDNITE MINE, SPOKANE, WASHINGTON

JONATHAN BARRINGTON AND PAUL F. KERR

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ABSTRACT

The Midnite Mine is located approximately 35 air miles northwest of Spokane, Washington, near the confluence of the Columbia and Spokane Rivers on the Spokane Indian Reservation. Uranium mineralization occurs in a zone along the contact between the Cretaceous Loon Lake granite and Precambrian metasediments. Ores appear to be found within and near associated fractures and shear zones. Secondary, oxidized uranium minerals, principally autunite and meta-autunite, lie above a fluctuating water table, while below this water table there occurs a zone of partially oxidized, sooty and compact uraninite. Sulfide mineralization is associated with the uraninite.

Associated zones of argillic alteration that contain kaolinite, illite, montmorillonite and intermingled adularia further indicate the action of

hydrothermal solutions. Botryoidal masses of marcasite and shrinkage cracks in the uraninite imply colloidal precipitation in the formation of the primary uranium ore. Ore deposition is inferred to have taken place at temperatures on the order of 300° C in a neutral or slightly acidic environment.

INTRODUCTION

THE Midnite Mine of the Dawn Mining Company lies about 35 air miles northwest of Spokane, Washington, near the village of Wellpinit, on the Spokane Indian Reservation. Several open cut uranium mines are set in an area of rounded hills punctuated locally by steep slopes a few miles northeast of the confluence of the Columbia and Spokane Rivers. The ore occurs at the contact between regionally metamorphosed Precambrian sediments and an intrusive Cretaceous granite and along fractures or shear zones which cross the contact. A zone of secondary uranium mineralization consisting principally of autunite and meta-autunite and a zone of primary uraninite lying below provide the source of the ore.

Discovery of uranium mineralization occurred in 1954 when the area was prospected with Geiger counters. Outcrops of the Precambrian schist were noted to yield anomalous, high counts and small amounts of yellowish-green radioactive mineralization were observed. The radioactive mineral was subsequently identified as meta-autunite. An extensive drilling program indicated the presence of sufficient uranium ore to warrant mining operations.

The first ore mined came from the upper, oxidized zone. A representative sample ran 0.48% U_3O_8 and others ran as high as 0.86% U_3O_8. The average uranium content of the first 700 tons shipped was 0.285% U_3O_8 (16). Since August, 1957, a 440-ton per day mill has been in operation nearby, at Ford, Washington. Through 1959 a total of 1,805,965 tons of waste were stripped, and 488,871 tons of ore mined.

Open pits have now been developed to the point where primary, sooty uraninite is being obtained from the lower zone in two pits, the Boyd No. 1 and the Boyd No. 2. Two more pits, the No. 2 pit and the Hill No. 3 pit are under development. A fifth operation on Hill No. 4 has been drilled but no further development is contemplated at present. Figure 1 shows a schematic layout of the mine area, illustrating the position of the pits as well as the various rock types and the trend of contacts.

The purpose of this study has been to establish the nature of the ore, the relationship of the associated argillic alteration and to examine the various factors responsible for ore distribution in the mine area. Hand specimens were collected in the summers of 1957 and 1958 and core samples have been made available by the Dawn Mining Company. Methods of examination have included differential thermal analysis, X-ray diffraction, X-ray spectrographic analyses and conventional microscope techniques.

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Mr. James Wilson of the Dawn Mining Company. Their cooperation has made this study possible. The assistance of the Division of Research and the Division of Raw Materials, U. S. Atomic Energy Commission is gratefully acknowledged. The constructive criticism and technical suggestions of the late Miss Peggy K. Hamilton of Columbia University were of great value in the laboratory.

REGIONAL GEOLOGY

The Midnite Mine lies within the Turtle Lake Quadrangle recently under study by the U. S. Geological Survey, a preliminary map by Becraft and Weis having been published in 1957. The major rock types consist of a thick section of Precambrian argillites, phyllites, quartzites, slates and dolomites separated by an erosional unconformity from Paleozoic quartzites, argillites and dolomitic marble. The sequence has been intruded by a granitic batholith composed of granites, granodiorites, alaskites and quartz monzonites, which has been tentatively assigned to the Cretaceous. In places glacial deposits and remnants of Tertiary lava flows overlie the older rocks.

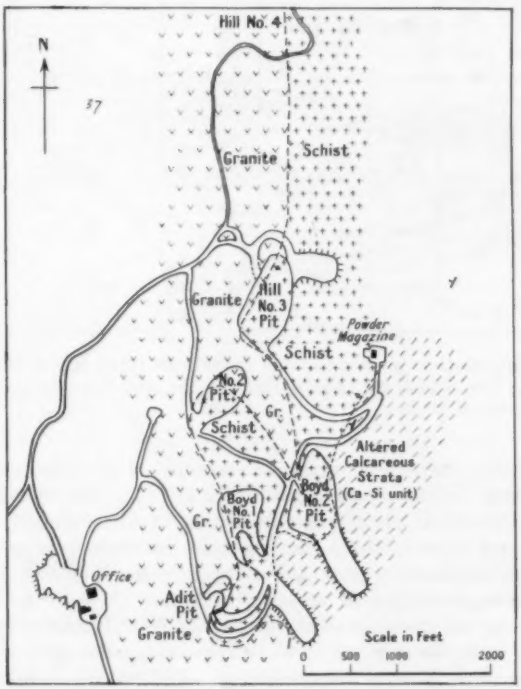


FIG. 1. General map of the Midnite Mine area. Mining operations occur at or near the contact between the granite and Precambrian metasediments.

The entire sequence of metasediments has a northeasterly trend with the older rocks on the east. In 1920, Charles Weaver carried out the first extensive study of the geology of the area, consisting of regional mapping and the assignment of names to various members of the sequence. The granite at the mine is part of Weaver's Loon Lake intrusive, a general name for the rock of the batholith. The metasediments are part of the Togo formation, according to Sheldon (29), and the latter forms a part of Weaver's Deer Trail argillites. The phyllite observed at the mine is presumably the Prichard schist, a member of the Togo formation.

ROCK TYPES

Three main rock types are encountered at the Midnite Mine. A granite member of the Loon Lake batholith forms tongues and ridges that intrude

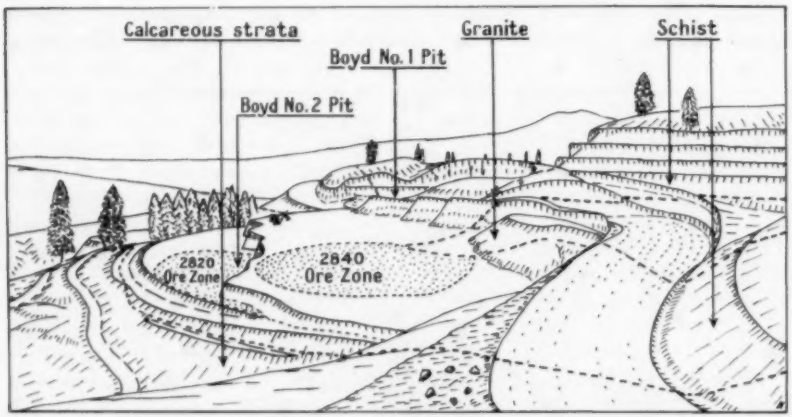


FIG. 2. The relative positions of the three rock types in the Boyd No. 2 pit, looking west. The schist lies above the granite and between the "calc-silica" rock and the igneous rock.

into and underlie the Precambrian formations. Two lithologic units may be distinguished within the Togo formation; (1) the so-called Prichard schist, and (2) a "calc-silica" rock consisting of alternating bands of dolomitic marble and more siliceous metamorphic minerals such as idocrase and garnet. These beds become progressively more calcareous and thicker toward the east. The approximate relationship of these three rock types, as observed during the development of the Boyd No. 2 pit, is shown in Figure 2.

The Loon Lake Granite.—The intrusive rock in the vicinity of the mine is a relatively acidic granite containing no amphibole, sphene, or pyroxene and showing small amounts of biotite. The quartz content is high, the plagioclase feldspar is about An_{12} and the alkali feldspar is perthitic, es-

pecially near the contact with the Precambrian formations. The approximate mineralogical composition as estimated from thin section examination is: quartz (55%), orthoclase (25%), plagioclase feldspar (10%) with small amounts of biotite, zircon, clay minerals and magnetite. The granite is generally equigranular and is composed primarily of anhedral crystals of perthitic orthoclase and quartz. It shows a progressively more intense argillic alteration close to the contact with the Prichard formation.

Dark smoky quartz may be observed in the granite near the contact with the metasediments and in the proximity of ore bodies. In the Adit Pit a range in intensity may be observed beginning with dark quartz close to the contact and progressing through lighter varieties until about one hundred feet from the contact, the quartz is almost clear. The dark coloration is unevenly distributed throughout the mineral. Similar smoky quartz is also noted in the Prichard phyllite.

Examination of the smoky quartz shows no perceptible variation from the normal optical properties of quartz. X-ray diffraction analysis of the quartz structure yields no unusual lattice measurements. The field distribution of the smoky quartz with uranium minerals suggests that the darkening may have been produced by natural radioactive bombardment. Wright and Bieler (34) report dark quartz in association with primary uranium mineralization in the Boulder batholith, but they ascribe the color of the quartz to inclusions of small quantities of microcrystalline opaques rather than to radioactive bombardment.

According to Przibram (27), colorless quartz becomes smoky under radium irradiation, the rate of coloration varying with different specimens and the exposure. Experiments by Mohler (24) and Forman (12), who obtained the absorption spectrum of X-ray colored quartz, further support the view that the coloration of smoky quartz may be attributed to radiation.

A sample of the dark quartz from a pegmatitic phase of the granite in the Adit Pit was bleached white by heating. A single grain weighing 0.516 grams was heated for 24 hours at 250° C with no change in color being noted. The temperature was then raised to 500° C. At the end of an additional 21 hours, the specimen had become milk white throughout. Przibram (27) considers such a reaction by dark quartz to heating as proof of coloration by radioactive irradiation.

The biotite in the granite has been altered, particularly near the contact with the phyllite. At a distance of one hundred feet from the contact, in the Boyd No. 1 pit, the biotite is relatively fresh. Here, it is subhedral and prismatic in habit and is pale brownish green. It is moderately absorptive and often contains small inclusions of zircon. As the contact is approached, the biotite becomes progressively more orange, more strongly pleochroic and stringers of chlorite are observed developed along the basal cleavage. Crystals of biotite are also broken into fibrous masses that are noticeably warped. The changes become most intense at the contact where bits of hematite and limonite staining are found in association with the disrupted prisms of the mica.

The feldspars also show progressive alteration as the contact is ap-

proached. In fresh granite orthoclase is present as anhedral crystals showing little twinning. The oligoclase appears as small subhedral prisms. As the contact is approached, these minerals become clouded with clay minerals, principally kaolinite. The kaolinite gives way to sericite and drilling samples taken from the contact and from nearby shear zones contain large amounts of greenish montmorillonite. Clay alteration of the granite has not always progressed to the same degree of intensity at all points along the contact. In some core samples, the granite is relatively fresh up to the contact with only a small amount of kaolinization. The granite ranges from a fine-grained to an almost pegmatitic texture and the most intense clay alteration is found in association with the coarser grained phases.

The Prichard Schist.—In the vicinity of the Midnite Mine, the Prichard schist is a highly siliceous metasediment that is essentially a phyllite. It shows foliation with large amounts of microcrystalline sericite lying in the plane of relict bedding where undisturbed by recrystallization. The rock has a fairly constant mineralogical composition with local variations being larger than any overall change within the formation. The principal minerals present, as estimated from thin section examination, are quartz (60%), muscovite (20%), pyrite (5%), kaolinite (5%), biotite (5%), chlorite (5%) and apatite.

The quartz is invariably equigranular, angular and subidioblastic, displaying characteristics frequently interpreted as indicative of a metasedimentary origin. In some sections, bands up to one centimeter thick, composed of equigranular crystals of this nature, run roughly parallel to the relict banding in the phyllite. The average width of the banding in the rock is only one or two millimeters, implying that the quartz bands are postsedimentary and may represent post-metamorphic introduction of quartz, possibly in association with ore deposition.

The dark, smoky quartz, which is readily observable in the granite in association with the contact and with ore bodies, is also found in the phyllite. However, in this rock there appear to be two varieties of quartz. Most of the quartz occurring in the relict bedding or as bands parallel to this bedding is clear. The smoky quartz is found in veins that cut across the banding at relatively sharp angles. In some sections, a vein of smoky quartz has been observed in contact with a stringer of clear quartz, a sharp boundary occurring between the two varieties.

The cross-cutting veins of smoky quartz are most noticeable in ore-bearing portions of the phyllite such as in the Boyd No. 1 pit where the veins have a high pyritic content. It appears that the smoky quartz, in the phyllite, represents a post-metamorphic and probably post-intrusive phase of silicification associated with the uranium mineralization.

The muscovite present was apparently formed during regional metamorphism of the original sediment. The crystals are all parallel to what appears to be relict sedimentary banding in the rock, giving it a distinct foliation. Any surface parallel to this banding displays a characteristic sheen resulting from the relatively abundant, fine-grained mica. All of the mica is xenoblastic, having its grain boundaries limited by the crystals of quartz

in the rock matrix. The muscovite is of such a fine-grained nature as to be sericitic.

Biotite and chlorite are oriented parallel to the muscovite foliation. The crystals are generally slightly smaller than those of the muscovite, being on the order of 0.05 mm in diameter. Biotite does not occur in noticeable amounts in those portions of the rock where chlorite is found. In certain drill holes a zone containing chlorite begins at the surface and extends to a depth of about 40 feet. At this point, the chlorite phase gives way to biotite, the latter mineral continuing in predominance to the contact with the granite at depth. No evidence of the alteration of one mineral to the other has been observed, the biotite always appearing as unaltered orange-brown crystals and the chlorite as equally unaltered pale green flakes. The biotite zone and the chlorite zone may represent two phases of low-grade regional metamorphism, one grading into the other. Biotite is usually regarded as representative of more intense metamorphism than chlorite (32), and the biotite zone, as noted, lies closer to the contact with the intrusive granite. The biotite zone may represent subjection of the original chlorite phase, produced by low grade, regional metamorphism, to contact metamorphism and possible metasomatism.

From the surface to a depth of about 50 feet, heavy limonite staining and veins of hematite are observed in the phyllite. The staining occurs around irregular masses of pyrite and appears to have been produced by heavy oxidation of this mineral and of magnetite. At greater depths such staining occurs commonly, but it is limited to cracks and fissures that have apparently acted as conduits allowing the introduction of unusual amounts of oxygen-bearing ground water. Veinlets of massive, hydrated iron oxides up to one-half centimeter in width have been produced in this manner. It is quite possible that some of these fissures also acted as a means of introducing the original iron sulfide-bearing solutions into the rock.

A highly disseminated sulfide phase is present in the phyllite. The sulfides, consisting primarily of pyrite and marcasite with minor amounts of arsenopyrite, chalcopyrite and sphalerite, occur as platy, anhedral crystals lying in the plane of the foliation in the rock. Pyrite and marcasite also fill microscopic veins and cavities that cut across the relict bedding. The amounts of arsenopyrite, chalcopyrite and sphalerite are small and are only detected under the microscope. Arsenopyrite appears to be the earliest sulfide, having been followed closely by the other ore minerals. There is little evidence of replacement of one sulfide by another, but there has been some replacement of the phyllite by the ore minerals.

Apatite is always present in the phyllite in small amounts. The crystals are small and subhedral prisms are well distributed in all sections studied. The mineral may have been the source of the phosphate in the autunite and meta-autunite that occur in the oxidation zone. If such is the case, evidence exists of mineral component transportation in the oxidized zone since autunite and meta-autunite are observed in the granite, though no apatite or other phosphorous-bearing mineral has been observed in that rock. Small amounts of clay minerals, principally kaolinite, are present in most sections.

The Calc-silica Rock.—The calc-silica rock is a pale blue-gray, showing relict sedimentary banding and effervescing readily with hydrochloric acid. It lies to the east of the phyllite and appears in the Boyd No. 2 pit.

In thin section the banding consists of alternate layers of coarsely crystalline dolomite and more siliceous material with an average mineralogical content of idocrase (60%), quartz (25%) and garnet (10%). Some clay, clinozoisite and wollastonite have also been observed. The idocrase occurs in both the silica-rich bands and in the recrystallized carbonate bands. The rock may represent regional metamorphism of a lime-rich sediment with superimposed contact metasomatism. It is broken and fractured in many places, the fracturing being filled with coarse grained recrystallized dolomite. Clay-rich horizons range from several inches to several feet in thickness and contain traces of sulfides indicating post-metamorphic hydrothermal activity.

STRUCTURE

The metasediments at the Midnite Mine form a long nose or tongue, running generally north and south, which is surrounded by granite on three sides. According to Sheldon (29), the granite extends under the metamorphosed sediments at angles from 30° to 70°. Drilling indicates that the

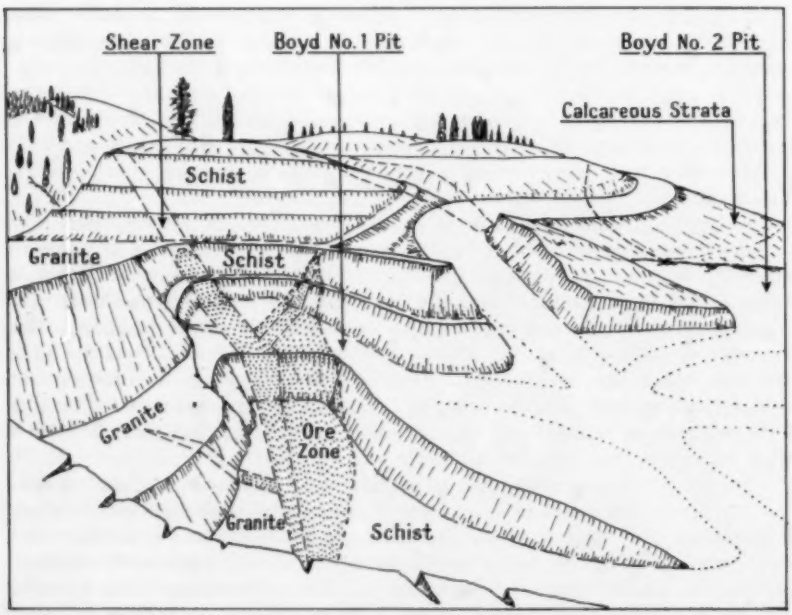


FIG. 3. Relation of ore to the contact and to shear zones in the Boyd No. 1 pit. Fractures extend from main shear zone into phyllite and granite.

contact becomes flat and that the metamorphics are only a few hundred feet thick. Further, the contact under the phyllite and the calc-silica rock is irregular, the granite having numerous ridges and depressions. Granite dikes and sills are common and generally conform to the bedding in the phyllite. The metamorphosed sediments lie in truncated, northeasterly striking folds with the entire series being overturned to the west.

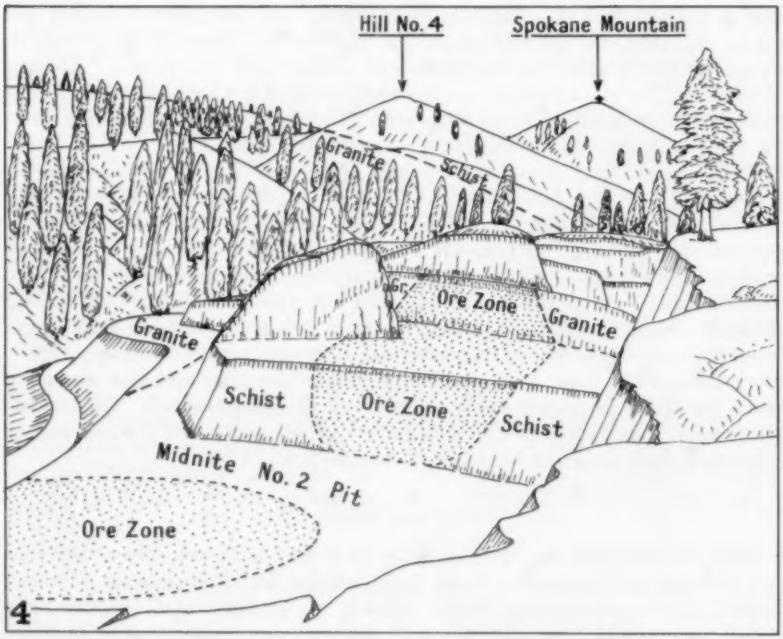
Faults and shear zones are common, especially in the region near the contact and in places have provided sites for ore deposition. Most of these fractures are steeply inclined and show little or no dip-slip movement. Apparently the fractures in the sediments are mostly pre-granite. The more prominent faults trend northeasterly and represent ruptures along fold axes. Smaller faults within the granite may be the result of differential cooling stresses. Sheldon (29) concludes that only a few of the later faults have acted as channelways for the hydrothermal, uranium-bearing solutions. However, most of the faults and shear zones show bleaching and clay alteration and some of the prominent shear zones are heavily mineralized. Figure 3 is a schematic illustration of the distribution of ore along the contact and in associated shear zones as observed in the Boyd No. 1 pit.

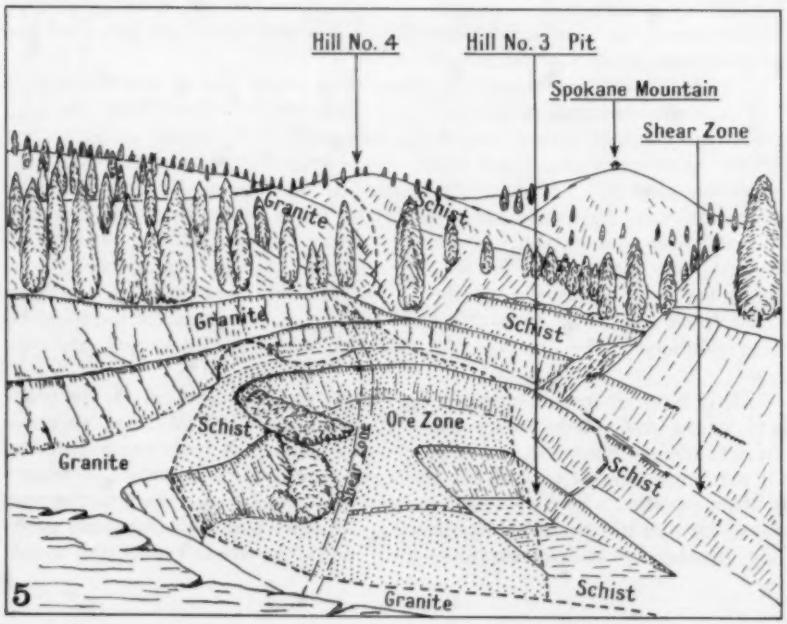
THE ORE BODIES

The ore bodies at the Midnite Mine lie at and in the vicinity of the contact between the Cretaceous Loon Lake granite and Precambrian Prichard schist. The upper portions of the deposits are composed of oxidized, secondary uranium-bearing minerals with autunite and meta-autunite predominating. At depth, sooty uraninite is encountered. Hard, vitreous samples of uranium oxide have been observed in a few drill cores and are described as specimens of primary pitchblende.

The individual ore bodies may range from a few feet to several hundred feet in length and from a few feet up to 200 feet in width. They are generally lenticular or canoe-shaped deposits with the greatest concentration of ore occurring at the point where the contact flattens out and continues under the phyllite. Sheldon (29) states that the ore can be very irregular in the oxidized secondary zone where the shape is influenced by bedding and schistosity, faults, shear zones, slips, dikes and generally any factors influencing the permeability of the rock. At the base of the oxidized zone and in the sooty uraninite zone, the ore becomes more restricted to the region of the faults and shear zones that have acted as the conduits for the mineralizing solutions. The ore does not appear to be restricted to any one rock type.

Eight more or less separate ore bodies are reported to occur on the property strung out intermittently along the contact. Four of these occur in the pits now in operation. A fifth, the adit deposit, is temporarily inactive. Of particular interest is a deposit indicated only by drilling, which is located in the calc-silica rock at a distance from the contact with the granite near the eastern end of the mine operations. At other points on the mine property, ore occurs in concentrations away from the contact in shear zones.


Hill No. 4
Spokane Mountain
Granite
Schist
Ore Zone
Granite
Granite
Schist
Ore Zone
Schist
Midnite No. 2 Pit
Ore Zone
4


Hill No. 4
Hill No. 3 Pit
Spokane Mountain
Shear Zone
Granite
Schist
Granite
Schist
Schist
Ore Zone
Granite
Shear Zone
Schist
Schist
Granite
5

Apparently the contact and some of the major shear zones and faults have acted as lines of weakness along which ore-bearing solutions have penetrated. The contact appears to provide the principal locus for ore deposition since the major ore bodies occur nearby or extend outward from the contact plane.

The relation of the ore bodies to the contact and their general geometry as exposed in the pits may be seen in Figures 2, 3, 4 and 5.

URANIUM MINERALIZATION

Both primary and secondary mineralization are observed at the Midnite mine. The primary minerals are uraninite and coffinite. The occurrence of coffinite without associated organic material is unusual in the western United States. Secondary minerals are meta-autunite, uranophane, zippeite, phosphuranylite, autunite, gummite, hebergite and torbernite. The uranium oxide was tentatively called primary pitchblende by Sheldon (29).

The sulfides in association with the uraninite have been identified as pyrite, marcasite, arsenopyrite, chalcopyrite and sphalerite. Molybdenite, in association with marcasite, has been observed in two drill core samples from the Boyd No. 2 pit. Molybdenum appears to be a fairly common associate in uranium ores, having been observed at several localities as, for example, at Marysvale, Utah (18), at Cameron, Arizona (15), and elsewhere on the Colorado Plateau. Traces of magnetite also occur with the sulfides. By far the most abundant sulfides are pyrite and marcasite with the marcasite being the mineral most closely associated with the uraninite. Everhart (11) shows sulfides such as these to be quite common at uranium localities, especially in vein deposits and in areas where hydrothermal deposition is indicated.

In a drill hole in the Boyd No. 2 pit, zones of intense clay alteration were observed in passing through the meta-sediments to the contact with the intrusive. Between the depths of 15 and 45 feet, in calc-silica rock above the phyllite, a zone of almost pure kaolinite was encountered. At the contact with the phyllite, at a depth of 55 feet, a small amount of illite and traces of montmorillonite were observed by means of X-ray diffraction analysis to be present with the white, chalky kaolinite. The phyllite was found to be relatively unaltered and the next clay zone was encountered at a depth of 117 feet where the calc-silica rock was once more encountered. Here the predominant clay mineral is montmorillonite with small amounts of illite. Ore grade deposits of uranium-bearing minerals were found in association with this montmorillonite zone. The association of uranium ore and montmorillonite continues to the contact with the granite at a depth of 160 feet, the clay becoming almost pure, greenish-tan montmorillonite. In the montmorillonite at the contact, molybdenite blebs and stringers have been observed. Clay

FIG. 4. Ore zone of the Midnite No. 2 pit. Ore occurs at or near the contact with the major position of the ore being located in the schist.

FIG. 5. Ore zone of the Hill No. 3 pit. The ore occurs principally in the granite in association with a clay-bearing shear zone.

alteration of this nature, displaying kaolinite, illite and montmorillonite in sequence, is frequently considered indicative of hydrothermal activity (17). Similar clay alteration zones in association with primary uranium mineralization in granodiorite is noted by Wright and Bieler (34) in the Boulder batholith, Montana.

The clay alteration is developed to the greatest degree in the calc-silica rock. In the granite, clay zones are observed in the regions near faults and shear zones, the alteration presumably having taken place at the time the mineralizing solutions were moving along these fractures.

At the surface, near the contact between the phyllite and the calc-silica rock, clay zones are exposed. X-ray diffraction analyses of various samples from these exposures show that adularia and a 3-T mica polymorph are present in the clays. These minerals are considered indicative of hydrothermal activity. Kerr (17) states that adularia is a significant feldspar that may form under hydrothermal conditions and it has been observed in close association with uranium oxide at Marysvale, Utah, where it is interpreted as an indication of alkaline conditions in which the alteration fluid had a high concentration of potassium and silica (18). The soda-rich nature of the granite and the presence of large amounts of introduced quartz in the phyllite suggest that similar conditions existed at the Midnite Mine during the ore-forming period.

Mineral synthesis investigations have determined the conditions under which clay minerals may be expected to form. Noll (26) showed that kaolinite may form in neutral, alkali free or in acidic alkali-bearing solutions below 400° C. According to Schwartz and Walcher (28) kaolinite must form between pH 4.5 and 5.2 at temperatures on the order of 300° C. Gruner (14) reported that muscovite (variety sericite) forms above 350° C and kaolinite below this temperature. Work performed by Noll (26) showed that montmorillonite may be expected to form from mixtures with alkali or alkali-earth metals when solutions have a high pH. Temperatures on the order of 300° C are indicated. These data would suggest hydrothermal solutions with temperatures in the range 300° to 350° C, the pH changing from slightly acidic to slightly alkaline as the temperature dropped.

Hydrothermal activity is indicated by the clay alteration at the mine. In addition, sulfides, principally molybdenite in association with marcasite, have been observed in clay zones near the contact with the granite. Marcasite is also found in close association with the uraninite. This would tend to indicate that the uranium has been contemporaneously deposited from moderate temperature, hydrothermal solutions with the sulfide phase.

URANINITE

X-ray diffraction data (Table 1) have been obtained for the sooty uraninite, which indicate a value of 5.372 Å for the unit cell dimension of the mineral. This value is somewhat smaller than the accepted unit cell dimension for uraninite of 5.46 to 5.47 Å and probably represents the oxidation of the uranium from the plus three and plus four to the smaller, more stable plus

six valence state (23, 13). Partial oxidation of primary, hydrothermal uraninite is indicated. Examination of the sooty uraninite using the X-ray spectrograph indicates that the material is almost pure uranium oxide, no trace of thorium being observed.

The uraninite occurs most commonly in association with marcasite, the association being confined primarily to the phyllite where a major portion of sulfide and uranium mineralization is found. Uraninite is observed to lie in the plane of foliation of the phyllite and to fill minute fractures cutting across this foliation, with or without the presence of the sulfides. When sulfides are present, they are confined primarily to the plane of foliation with

TABLE 1

X-RAY DIFFRACTION DATA FOR SOOTY URANINITE

(a)		(b)		(c)		Midnite Mine*	
d(Å)	I	d(Å)	I	d(Å)	I	d(Å)	I
3.11	7	3.16	10	3.16	10	3.090	10
2.70	6	2.73	5	2.74	5	2.686	5
1.92	10	1.94	8	1.93	5	1.900	5
1.63	10	1.65	8	1.65	5	1.62	4
1.56	2	1.58	2	1.58	1	1.54	2
1.49	1					1.49	1
1.36	2	1.37	1	1.37	1	1.38	1
1.25	5	1.25	3	1.26	2	1.33	2
1.21	5	1.22	3			1.22	2
1.15	2	1.17	3				
1.11	5	1.12	3	1.12	2	1.11	1
1.04	4	1.05	3	1.05	2	1.04	2
$a_0 = 5.40$		$a_0 = 5.46$		$a_0 = 5.47$		$a_0 = 5.372$	

(a) Elias Mine, Joachimsthal, Bohemia.
(b) Arnott, 1950, p. 388.
(c) Swanson and Fuyat, NBS Circular 539, v. II, 1953, p. 33.
* Copper radiation, nickel filter.

only the marcasite being found in fractures and cavities in any amount. The uraninite generally occurs with accompanying sulfides.

THE URANINITE-MARCASITE ASSOCIATION

Uraninite and marcasite appear to have been deposited contemporaneously and by the same process. The walls of microfractures or small cavities in the phyllite that contain these minerals commonly have a thin veneer of marcasite. A layer of uraninite commonly overlies this veneer, followed by a second layer of marcasite. In rare cases the alternating layers of ore mineral bands may total as many as five or six. The layers are mostly of a fairly constant thickness with the uraninite showing the greatest deviation. In small cavities a common association is a wall veneer of marcasite overlain by a layer of uraninite of equal or slightly smaller thickness with a central core of marcasite, as illustrated in Figure 6, and in portions of the vein as

shown in Figure 7. In many veins there is a deposit of marcasite on only one wall, the rest of the vein being filled with uraninite. In Figure 7, two small cavities can be seen at the upper right showing a marcasite layer on the walls and a marcasite core. The marcasite is the whitish mineral and

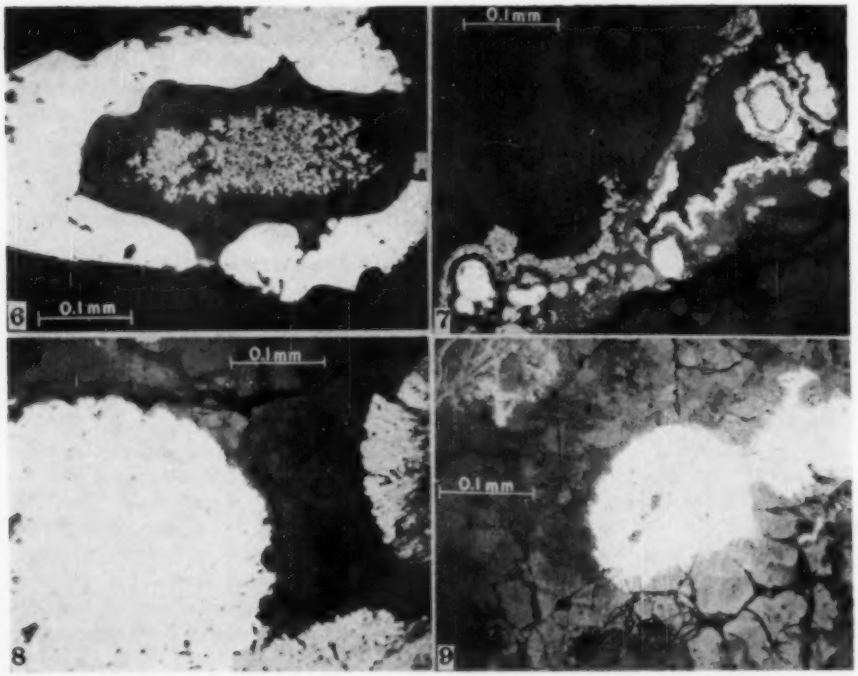


FIG. 6. Cavity in phyllite showing the common sequence marcasite-uraninite-marcasite with the star-shaped, acicular marcasite crystals of the core considered to be the latest mineral phase.

FIG. 7. Small veins and cavities in the phyllite. A marcasite layer lines the walls with the majority of the openings being filled with uraninite. Marcasite cores and masses in the uraninite indicate a second stage of marcasite deposition.

FIG. 8. Botryoidal masses of marcasite in the phyllite. The radial arrangement of component crystals is characteristic of the marcasite and suggests a colloidal origin.

FIG. 9. Shrinkage cracks in uraninite surrounding botryoidal marcasite.

the uraninite is the closely associated dark gray mineral, slightly lighter in color than the general background. Uraninite fills the center of the small vein in the upper center of the figure and is the major mineral in the larger vein running across the lower part of the illustration. As can be seen, small irregular masses of marcasite appear in the uraninite. These may represent

a late stage, possibly post-uraninite, of marcasite deposition. The boundary between the two minerals is never sharp, but appears to represent a transition from one dominant depositional phase to another as a result of a change in temperature or chemical composition of the depositing solution. Fluctuations of the physical and chemical characteristics of the original solution are pictured as being responsible for the layered depositional sequence.

A similar relationship between marcasite and uranium oxide has been observed at the Los Ochos Mine, Saguache County, Colorado, by Derzay (10) and by Malan and Ranspot (21). A sequence of marcasite depositional periods is considered the source of the association at that mine.

COLLOIDAL DEPOSITION

Certain physical aspects of the uraninite and the marcasite suggest formation from a colloidal system. Commonly the marcasite appears as spherical or botryoidal masses that show a radial arrangement of the crystals within the mass as illustrated in Figure 8. Similar, but smaller masses are found included in veins composed primarily of uraninite. In addition to the habit of the marcasite, which is commonly interpreted as indicating colloidal origin (4), microscopic fractures reminiscent of drying or shrinkage cracks are observed in the uraninite as in Figure 9. According to Anderson (2):

> Colloform structures especially with the development of concentric and radial cracks are regarded by Lindgren (1925, p. 255) as strong indications of colloidal ancestry. Both Lindgren (1925, p. 247–262) and Boydell (1924; 1928) have been strong advocates of the influence of colloidal solutions in the formation of mineral deposits, and they as well as Clark and Menaul (1916, p. 37–41) have shown that highly dispersed colloids may penetrate rock openings as easily as solutions and may take part in replacement. Boydell (1928, p. 117) further has suggested a possible mechanism by which ore of colloidal origin may be formed and has pointed out that a disperse system may contain within itself most of the factors necessary for precipitation and thus is less dependent upon external causes than an electrolytic solution.

DEPOSITIONAL ENVIRONMENT

A number of marcasite masses have been observed whose centers are apparently composed of pyrite. These masses are interpreted as representing a transition phase between conditions favorable to the deposition of pyrite and those favorable to the deposition of marcasite and, presumably, uraninite. Miller (22) reports that uranium oxide may be precipitated from solutions by the action of hydrogen sulfide. Working with a pH of seven, he was able to precipitate fine-grained uraninite (pitchblende) from solution between temperatures of 25° and 215° C. This would indicate not only that the sulfide phase may have acted as a precipitant of the uranium oxide, but that the mineral could have been deposited at low temperatures in a near neutral environment. Pyrite is generally considered as indicative of temperatures above 450° C whereas its monotrope, marcasite, forms at temperatures below this and in an acid environment (1), the temperature of

formation decreasing with increasing pH. Kopp and Kerr (19) have shown that marcasite is definitely unstable above a temperature of about 460° C. The evidence indicates that the uraninite formed as a colloidal precipitate at temperatures somewhat below this temperature and in a slightly acid environment. There may have been little change in pH, the depositional sequence of pyrite, marcasite, uraninite, marcasite being a result of a general decrease in temperature with time.

Since the uraninite at the Midnite Mine apparently consists of particles of colloidal size and neither thorium nor lead occur in discernable quantities within the mineral, it may be better referred to as pitchblende, especially in the primary, unoxidized state.

Frondel (13) feels that the name pitchblende should be reserved for microcrystalline, primary uranium oxide of this nature. He notes that such material commonly contains relatively small amounts of thorium and lead.

CONCLUSION

The uranium-bearing ore at the Midnite Mine is of primary, moderate temperature, hydrothermal origin. Part of this has been converted to secondary, oxidized mineralization.

Ore genesis seems to have begun with the introduction of hydrothermal solutions, possibly but not necessarily, representing a late magmatic stage associated with the intrusive Loon Lake granite, along the contacts between three rock types and in related fractures, faults, and shear zones. Pyrite may be expected to have been deposited from the earlier, higher temperature solutions and the extensive distribution of this mineral suggests a widespread penetration of such. Solution temperatures were at least below 450° C and possibly considerably lower and the environment may have been somewhat acidic. As the system cooled, marcasite began to be precipitated in place of pyrite. Fine-grained uraninite was formed at the same time as were, probably, the small amounts of chalcopyrite and sphalerite with the sulfide phase possibly acting as the precipitating agent for the uranium oxide. Colloidal deposition of marcasite and uraninite may have occurred at any temperature below 450° C but most probably took place near 300° C. Molybdenite represents a comparatively high temperature mineral phase deposited near the contact where sufficient temperatures may be expected to have been maintained. Arsenopyrite and excess silica accompanied the first formed pyrite.

The paragenetic sequence of metallic mineral formation appears to be molybdenite, arsenopyrite, pyrite, marcasite, uraninite, marcasite, coinciding with a decrease in temperature and a possible retarded increase in pH. Argillic alteration in the form of kaolinite and illite preceded uranium deposition with the illite forming in the higher temperature region nearer the contact. Montmorillonite formed during and following the precipitation of uraninite when temperatures were lower and the environment possibly had become slightly alkaline. The large amounts of montmorillonite at and near the contact indicate that low temperature-moderate pH conditions were

maintained for a relatively long period of time and this could have been the predominant environment during ore deposition.

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BIOGENIC SULFIDES [1]

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ABSTRACT

Experiments have been carried out at the laboratory of the Bureau of Mineral Resources in Canberra on the preparation of sulfide minerals by biological methods with the following results:

a. Covellite, digenite, argentite, sphalerite and galena were prepared by bacterial sulfate reduction in artificial seawater on hydrogen and lactate media from carbonates, oxycarbonates and, in the case of silver, from the chloride. Chrysocolla was also used.

b. While nickel and cobalt yielded black sulfides, powder diagrams yielded no identifiable mineral.

c. Rhodochrosite and mercuric carbonate did not produce sulfides.

d. Mixtures of iron and copper oxides always yielded iron sulfides plus covellite. Neither bornite nor chalcopyrite could be obtained.

INTRODUCTION

ALMOST 130 years ago Daubrée, followed by de Sénarmont (8) endeavoured to prepare minerals by chemical methods. "Synthetic" mineralogy has become an integral part of this discipline. Several cases could be cited in

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which truly biogenic minerals were obtained; but a systematic approach to biosynthesis of minerals is lacking.

Many biological reactions are in the nature of accumulations, by which is meant a manifold concentration, by the organism, of an element from the outer environment. These reactions cannot be repeated by simple chemical means. Some oxidative reactions, furthered by micro-organisms, may be duplicated in the laboratory. Often, the rate of the chemical reaction is much lower than that of the biological reaction. Reductions of inorganic compounds are known as industrial and laboratory processes and may be carried out under sterile conditions. Exceptions to this are, of course, the reduction of carbon dioxide to sugars, which has never been achieved in the laboratory, and the reduction of sulfates to sulfides, which can only take place in the wet way by very roundabout methods.

In nature, the sulfate reduction is invariably bacterial, whereas the reduction of sulfur to H_2S may be achieved in a variety of ways. In this paper the formation of sulfide minerals by sulfate reduction is considered.

From the positive results obtained it may be concluded that, under certain natural conditions, several sulfide minerals may be formed by sulfate reduction. We are sure that our failure to obtain results with nickel and cobalt salts is rather due to our ineptitude than indicative of some fundamental natural phenomenon. Some of our results are contrary to theory, others cannot be duplicated by chemical means. However, it would be too early to designate sulfate reduction as a main factor in ore formation before we have adduced more arguments. The greatest difficulty seems to be the concentration factor. We know of very few places (e.g., near Pernatty Lagoon, S.A.) where a metal (copper) is present in sufficient quantities in the oxidized form to account for an accumulation of sulfides. This accumulation requires a still unstudied mechanism.

BIOLOGICAL AND CHEMICAL APPROACH

"Synthetic" mineralogy probably finds its origin in a publication of W. B. and R. E. Rogers, who, in 1848, described the action of water at a reasonable temperature (60° C), on minerals (8). They emphasized the role of CO_2 as a solvent. The synthetic mineralogy, as developed by Daubrée (articles in the Comptes Rendus 1849–1864, culminating in his Etude Synthétique de Géologie Experimentale (1876), as well as the contemporaneous work of H. de Sénarmont (15), is concerned exclusively with high-temperature reactions, and the results cannot be applied to processes taking place in the sedimentary environment. Syntheses "in the wet way" have remained rare. Of the 56 artificial syntheses of simple sulfides mentioned in Dana's handbook (9), 48 describe thermal reactions and only 8 are concerned with aqueous, low-temperature systems. We cannot help but feel that the support of synthetic mineralogy has been chiefly of use to those studying hydrothermal and magmatic reactions, and that the aqueous environment has been neglected. Possibly this is one of the reasons why, in the study of ore-bodies, there has been, maybe, a slight over-estimation of the magmatic and hydro-

thermal factors. Moreover, these thermal systems apply to temperatures and pressures which, as independent variables, have been studied only in a few cases, e.g., Allan et al. (2) for the pyrite system, Juza and Bilz (11) for the sulfur-sulfide system. About the thermodynamic systems in these regions we are ill-informed. We do not even know whether the free energy and pH concepts, derived for the normal aqueous environment, apply at high temperatures and pressures.

At the beginning of this century, after the work of the (chiefly) French chemists, it was comfortably concluded that the composition of the inorganic environment was pretty well known. This was an opportune thought, as attention could be diverted to the more "modern" things. We know now that this conclusion was highly premature. The period of this old-fashioned "bread and butter" chemistry is by no means over: free iodine, iodates, nitrous oxide, perchlorate, and hydrogen peroxide, as found since, are only an expression of the whim of the investigator and not a systematic attempt to catalogue, as it were, the inorganic environment. Synthetic mineralogy will remain highly one-sided if such a survey remains incomplete, apart from the fact of our predilection for thermal reactions, which has also been detrimental to the development of our knowledge of the sedimentary environment.

In one of his many prophetic statements Pasteur said that it seemed to him that the influence of the infinitely small (organisms) was infinitely great. A century ago geology was a comfortably "sterile" science, in spite of palaeontology and apart from a few inopportune and disobliging exceptions like coal mines and coral reefs. Under the influence of such masters as Winogradsky and Beijerinck this picture has changed completely. It may be said that the pendulum has swung to the other extreme position; there is a tendency now to ascribe a number of geological processes to microbial action without a thorough investigation of the geochemical and geobiological factors involved. Vague statements as to the virtues of micro-organisms in geological happenings are of very little use to us. On the contrary, as they are discursive, and often not based on experiment, they give welcome fuel to those critics, who, subconsciously perhaps, want to maintain the "sterile" *status quo ante*. There is ample experimental evidence to show that many sedimentary processes are abiological; the oxidation of pyrite to ferrous sulfate and of the iron monosulfides to sulfur and hematite have been shown to take place spontaneously under sterile conditions; there is no need to invoke bacterial action to account for them. A synthetic mineralogy, based upon biological reactions, has to take this into account.

A systematic approach to a "biological" mineralogy has not been made. The biological formation of limestone by coral animals and by coral algae was proposed before Darwin wrote his classical monograph and both aragonite and calcite were soon recognized as biological products. A special bacillus was thought by Drew (10) to be active in lime deposition and his *"Bacillus calcic"* has since haunted geological literature, although a special lime-depositing bacterium does not exist. Alderman (1) has shown that dolomite may be precipitated by the photosynthetic action of plants. The biological origin of the Texas sulfur deposits was proposed by Tan Tek Hok

(16), as long ago as 1927; this opinion has since been confirmed. Miller (13) succeeded in preparing various metal sulfides by sulfate reduction. He failed to obtain copper sulfide and no specific minerals were identified. Much more scattered evidence may be adduced, but a systematic approach has been lacking.

BIOLOGICAL AND CHEMICAL PROCESSES

As stated above, happenings in the aqueous sedimentary environment are partly biological, partly chemical. There are, amongst the geobiological processes, many that may be reproduced in the laboratory by chemical means. In the absence of bacteria many oxidations may proceed, albeit with reduced velocity, such as the oxidation of ferrous to ferric sulfate (unpublished) and oxidation of sulfur. Certain reductions are also spontaneous, e.g., the formation of H_2S from sulfur. The reduction is exothermic, and the beneficial effect of sulfur dust in the treatment of plant disease has been ascribed to this process. There are, however, biogenic reactions that cannot be easily reproduced in the laboratory: for instance, the photosynthetic carbon dioxide assimilation has eluded, thus far, any attempts at reproduction *in vitro*.

Amongst those that require unusual substances, acting at boiling temperature, in order to proceed, we may mention the reduction of sulfate to sulfuretted hydrogen. We realize, since 1895, that bacterial agencies carry out this reduction at room temperature. Keeping in mind the enormous quantities of ferrous sulfides occurring in the black muds in estuaries and elsewhere, it appears that this reaction is of prime geochemical importance. Before the discovery of the causative organism, in 1895, by Beijerinck (7), the handbooks on hygiene and on water treatment ascribed the occurrence of these sulfides to the decomposition of proteins; but, contrary to the opinion of some recent biochemists, proteins are very scarce in the natural aqueous environment. Most of the bacteria in these environments live on a minimum diet, and the juicy culture media, usually prepared by the bacteriologist, containing glucose, or peptone (or even more complicated substances in medical bacteriology), are hardly ever met with in the natural environment. This is why those forms that may develop without organic substances (the autotrophs) come to the fore in the natural environment.

SULFATE REDUCTION

General.—Desulphovibrio desulfuricans or *Clostridium desulfuricans* is the chief agent in the reduction of sulfates. It is an anaerobe. Baas Becking and Wood (3) found that it cannot occur under a pH of 4.2 (peat bogs), and Kaplan (private communication) found it at pH's well over 10 in mud from Searles Lake, California. The highest electrode potential at which it may develop is + 110 millivolts, a number since confirmed by more extensive tests. It may actually generate potentials as low as − 500 millivolts. There is evidence that, in this case, the cause of these low potentials is not the sulfuretted hydrogen but an addition compound of ferrous sulfide and sulfuretted hydrogen (4). Like all *Clostridium*-like organisms, the microbe is a spore

former and, under certain conditions, highly thermotolerant. Like *Clostridium pastorianum* it is able to reduce atmospheric nitrogen to the ammonia level. Its development is apparently inhibited in brines rich in magnesium salts, and selenates (maybe because of a competitive action) also inhibit the reduction (14).

In the highmoor waters of Tasmania sulfate reducers were not encountered. This is apparently due to the almost total absence of sulfate in these waters, for addition of sulfate to the moor waters yielded sulfate reduction. Certain strains of the sulfate reducers are able to persist and develop in an inorganic

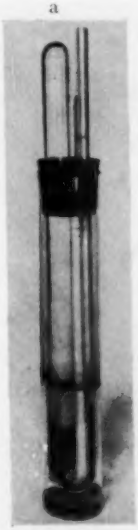

FIG. 1. Sulfate reducing bacteria growing on hydrogen. The tube to the left is filled with hydrogen by the tube on the right. Formation of black iron sulfide at a distance both from the hydrogen and the air-meniscus. The medium is filtered sterile seawater, to which is added some ammonium magnesium phosphate.

medium, if hydrogen is provided. This autotrophic existence is probably more common than has been assumed. Most experimental work has been carried out with organic media, lactate or acetate being most suitable hydrogen donors. Figure 1 shows the development of a purified culture of sulfate reducers in a hydrogen atmosphere on filtered seawater (Gunnamatta Bay, N.S.W.) to which some ammonium magnesium phosphate was added. It is also possible to generate hydrogen in the seawater by means of steelwool or of zinc wire (Fig. 2). If the presence of iron compounds in the medium is undesirable, the steelwool may be wrapped in cellophane and evacuated to remove the air. The iron compounds, insoluble at the pH of seawater,

will remain inside while the hydrogen will diffuse out. In our work we made use of a strain capable of developing either on hydrogen or on organic matter; this was isolated from estuarine mud at Port Hacking, N.S.W. After three transfers on a steelwool medium the culture was used for the production of metal sulfides. Although, in laboratory bacteriology, the use of pure cultures is indicated, in the study of natural processes (18) such a practice may lead to erroneous results, as in nature we usually find an assemblage of microbes instead of one actor. In our work this assemblage has probably been reduced to few, and maybe to one component, owing to

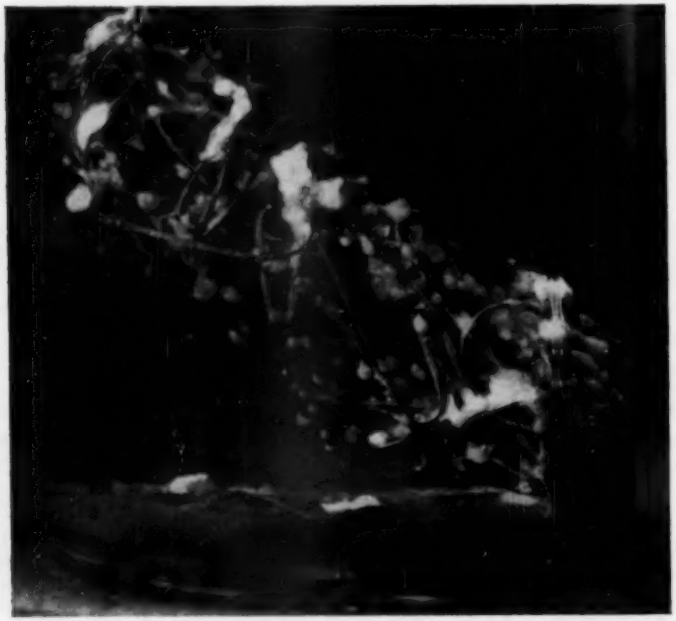

FIG. 2. Formation of zinc sulfide from zinc wire. The medium is filtered, sterile, seawater with the addition of ammonium magnesium phosphate. Bacteria develop on the hydrogen generated by the zinc.

the special nature of the medium into which they were repeatedly transferred. Recent work on the oxidation of pyrite (unpublished) has shown the complexity of the assemblage of iron and sulfur bacteria taking part in this process. It is likely, however, that sulfate reduction, as far as the number of organisms is concerned, is more like a monologue than a play.

Ferrous Sulfide from Metallic Iron.—In active cultures with steelwool prepared with artificial seawater, black sulfide is formed within one week at 30° C. The artificial seawater, which may be sterilized by heat, was prepared as follows:

Tapwater	100 g
NaCl	3 g
Ammonium magnesium phosphate	.075 g
Potassium sulphate	.350 g
Soil extract	5 ml
Calcium carbonate	10 g

(natural seawater is saturated with lime)

After autoclaving, the suspension was shaken for 24 hours, the lime was allowed to settle and the supernatant decanted. The solution showed a pH of 8.2, total base 2.5 10^{-3}n, like seawater. An adequate supply of both sulfate and bicarbonate was present. For a 250 ml stoppered bottle, 1 g of steelwool, degreased with carbon tetrachloride, was added. The black sulfides formed oxidize rapidly in air with the formation of iron oxide and sulfur (see also 17). When these sulfides were dehydrated by repeated treatment with absolute alcohol, a black powder was obtained, which could be kept for weeks in a sealed tube. In a moist atmosphere it oxidized rapidly and even the manipulations necessary for the preparation of the X-ray photograph caused enough change to prevent an interpretation of the powder diffraction pattern. Iron powder may be substituted for steel wool, although the reaction is slower, probably owing to the reduction in surface. When using organic media (artificial seawater) with 1 percent sodium lactate or acetate, iron was added to the medium as strengite or as hematite. The phosphate was the more successful.

Pyrite and Marcasite from the Monosulfides.—This process is an oxidation and considered by us as a hydrogen donation to an external acceptor. However, experiments on this process are still under way and it would be premature to report on them here.

Covellite from Malachite via Copper.—Miller (13) failed to obtain sulfate reduction in the presence of copper hydroxy carbonate. We used copper phosphate, without success, but in our experiments, malachite apparently yielded only little soluble copper and the toxic effect was minimized. Using malachite, metallic copper appeared in both steelwool acetate and lactate cultures within three days incubation at 30° C. A black precipitate appeared after 5–7 days. This precipitate was digested with 10 percent acetic acid and centrifuged and washed five times. The X-ray powder pattern was that of covellite. Bateman (6) postulates its supergene formation from H_2S and copper sulfate. This cannot occur as a biological process, as copper sulfate is highly toxic to life.

TABLE 1

POWDER DATA FOR COVELLITE

Data from the literature							
d/n	3.26	3.03	2.81	2.71	1.89	1.73	1.56
I	12	20	60	14	100	10	50
From hydrogen 15.4.59							
d/n	3.19	3.03	2.78	2.71	1.89	1.73	1.56
I	10	50	40	10	100	5	10

Covellite from Chrysocolla.—Pernatty Lagoon (S.A.) contains a strong brine from which acid-insoluble black sulfides may be separated. When this lagoon was visited (May, 1958 with Mr. Haddon King and Mr. D. O'Driscoll) the abundance of copper and of manganese ore in the surrounding hills appeared to be most striking. The copper was chiefly present as silicate (chrysocolla). On a lactate medium with artificial seawater chrysocolla proved to be sufficiently insoluble to allow sulfate reduction to take

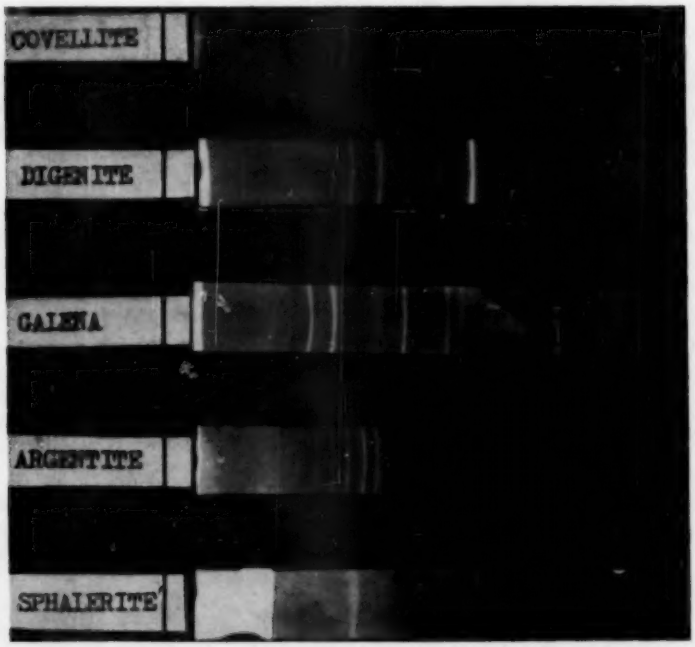

FIG. 3. Minerals generated from the carbonates by sulfate reduction in hydrogen or lactate containing seawater. The X-ray powder diagrams were prepared by means of a copper target, except for the sphalerite, where a cobalt target was used. The lines in the sphalerite diffraction diagram are less well defined owing to the admixture of other substances. The photographs were taken by Messrs. Bayly and Thomas in the laboratory of Mr. Roberts, B.M.R. The black inked line indicates the centers of the diagrams.

place. After a few weeks a copious black precipitate was formed, which consisted of covellite. The abundance of chrysocolla in the region could result in the formation of a large amount of covellite if the water level should rise, and anaerobic conditions prevail. This is the only case observed by us where enough oxidized ore was present to allow for an appreciable accumulation of sulfide to be formed under appropriate conditions.

Digenite from Cuprous Oxide.—Chalcocite may be prepared by the action

of heat upon H_2S and cuprous salts (15). Existing claims for its preparation in the wet way have been discredited. Bacteria, though not causing the formation of chalcocite, actually form the cuprous-cupric sulfide digenite when cuprous oxide is subjected to sulfate reduction. A lactate medium was used and the formation of the digenite preceded without the visible intermediate of native copper. The cuprous oxide was prepared by the reduction of an alkaline copper sulfate solution in the presence of tartrate by glucose. The reaction takes slightly longer than the formation of covellite from malachite (about 10 days at 30° C). The X-ray powder diffraction patterns (see also Fig. 3) were convincing.

TABLE 2

POWDER DATA FOR DIGENITE

Data from the literature									
d/n	3.20	2.78	2.17	1.96	1.67	1.39	1.25	1.13	1.07
I.	20	30	10	100	20	10	10	20	10
Culture 25.6.59									
d/n	3.19	2.75	2.16	1.95	1.67	1.38	—	1.13	1.06
I.	30	30	5	100	20	5	—	10	5

Argentite.—Both from the chloride and from the carbonate silver sulfide was formed on acetate and on lactate media. The typical purple color of native silver appeared first, although the cultures were placed in a dark incubator. With the increase in sulfide the native silver seemed to decrease. The sulfide was extracted with ammonia and washed several times after centrifuging, and the powder spectrogram obtained. About the identity of the product formed with argentite there is no doubt, as the following results show:

TABLE 3

POWDER DATA FOR ARGENTITE

Data from the literature									
d/n	3.40	3.08	2.83	2.59	2.43	2.37	2.21	2.08	1.71
I.	40	40	80	100	80	60	10	10	10
Black precipitate 25.6.59									
d/n	3.42	3.08	2.85	2.60	2.45	2.39	2.22	2.09	1.72
I.	10	20	20	100	60	20	10	10	10

Though several authors agree about the presence of argentite in supergene environments, Bateman (6, p. 39) holds that argentite and acanthite represent respectively the high and low-temperature forms of Ag_2S with an inversion point at 179° C. According to him much of what is called argentite in the supergene environment is really acanthite. Nevertheless, bacteria undoubtedly prepare argentite from Silver chloride and silver carbonate at low temperaures.

Galena.—This is probably the easiest sulfide to make by bacterial sulfate reduction. It is formed within four days at 30° C in media containing either hydrogen, lactate, or acetate. Both the carbonate and the hydroxycarbonate

may serve as a source of lead. The precipitate is easily cleaned in weak acid after removal of the carbonate with 10% KOH. The identification is certain, as the following table shows:

TABLE 4

POWDER DATA FOR GALENA

Data from literature								
d/n	3.42	2.96	2.08	1.79	1.71	1.36	1.33	1.22
I.	80	100	90	90	80	70	90	90
Precipitate 25.6.59								
d/n	3.41	2.95	2.10	1.79	1.71	1.36	1.33	1.21
I.	80	100	60	40	20	10	20	10

Sphalerite.—The active bacterial culture used in these experiments developed on artificial seawater without organic matter, when zinc wire was supplied (Fig. 2). White blobs formed on the wire after 3 weeks at ca. 20° C. These blobs developed H_2S when treated with acid and formed gas with sodium azide-iodine. Apparently a sulfide was formed that was assumed to be sphalerite, as the occurrence of wurtzite is unlikely at these low temperatures. As free zinc does not occur in nature, the experiment has little geobiological significance. It only shows that the strain of sulfate reducers used by us is able to utilize hydrogen and it provides us with a method for the culture of sulfate-reducing bacteria if the use of iron has to be avoided.

Sphalerite from Smithsonite.—Although a sulfide was formed within a week at 30° C on organic media, its identity with sphalerite could not, at first, be established, as the sulfide is soluble in weak acid. Because of this, a large amount of smithsonite remained in the precipitate. Using older cultures and gravity separation, followed by repeated centrifugation, we finally obtained a light gray material that yielded a rather blurred powder diffraction pattern with the characteristics of sphalerite. According to Bateman (6), however, this mineral is never of supergene origin in ore deposits.

TABLE 5

X-RAY POWDER DATA FOR SPHALERITE

Type specimen									
d/n	3.95	3.12	2.70	1.91	1.63	1.56	1.35	1.24	1.21
I.	30	100	70	90	90	30	70	80	30
1.11	1.04								
70	70								
From culture									
d/n		3.12	2.70	1.91	1.63		1.35	1.24	
I.		100	40	100	90		10	20	
1.10	1.04								
20	20								

Negative or Uncertain Results.—Though copious black precipitations were formed when nickel carbonate was incubated in organic media and though positive sulfide tests were obtained on these precipitates, we have

been unable to prepare an identifiable powder diagram from them. Cobalt carbonate behaved in a similar way.

Mercuric carbonate could not be reduced to cinnabar by bacteria. In this case no H_2S was formed. The toxicity of the mercury may account for this.

Although copious sulfate reduction occurred in cultures with rhodochrosite, neither alabandite nor hauerite was present in the precipitates. As will be stated in the discussion of the results, the electrode potential generated by the bacteria must have been too high to allow for the formation of these sulfides. As this conclusion is entirely based on free energy values and not on experimentation, the absence of the manganese sulfides in the final preparation may equally well have been due to our inexpert handling of the samples.

Failure to Produce Bornite and Chalcopyrite.—Using organic media and combinations of cuprous oxide or malachite to which we added either haematite or lepidocrocite, the black precipitates formed never showed the powder spectra of the copper-iron sulfides, but only the spectrum of covellite. These experiments, carried out at 30° C, were repeated under a variety of external conditions with the same results. This is important as both bornite and chalcopyrite are classed as hypogene.

The pioneer work on the formation of sulfides was done by Miller (13), who obtained sulfides of antimony, bismuth, cobalt, cadmium, iron, lead, nickel, and zinc by sulfate reduction, the latter two with difficulty. No positive identification of the products was made, apart from titration of the liberated H_2S after acid treatment. Miller failed to obtain sulfate reduction in the presence of malachite, while we found this compound to be a suitable source for covellite. The discrepancy in our results may be due to a difference in strains or to a difference in culture media. Miller used 1% NaCl whereas we used 3 percent, and, in his cultures, the sulfate concentration was about 6–10 times higher than in the artificial seawater used in our work; he used higher lactate concentrations as well. The influence of the chloride and the sulfate concentration has to be investigated further. As appears from this paper, unidentifiable sulfides were formed from nickel and cobalt salts. Without a proper X-ray identification the work has little significance.

DISCUSSION

The formation of native copper and of native silver as a "half-way house" between the oxidized and the reduced state is significant. Silver is definitely supergene (8) and may very well be formed in a way similar to that appearing in our experiments. The formation of native silver from its sulfides is called "a reduction" by Clarke, although it is definitely an oxidation. At very low potentials, below the potential region of the sulfide, there may be another zone in which native silver is stable; this region should be definitely magmatic, however.

In order to obtain an overall picture of our results the electrode potentials of the reaction sulfide-sulfate were calculated from the free energy data (12).

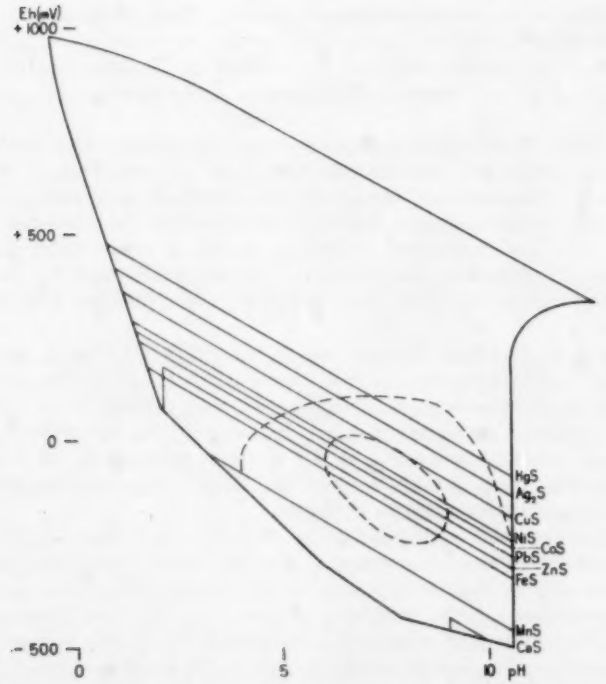

FIG. 4. Equilibrium lines between sulfides and sulfates. See Table 7. The upper hatched line shows the limit of sulfate reduction, the hatched area represents values encountered normally. The outer boundary represents the limit of the natural aqueous milieu.

The equilibrium lines for 25° C are drawn within the confines of the natural aqueous environment as outlined by Baas Becking, Kaplan, and Moore (in press) and by Baas Becking and Moore (unpubl.). Table 7 shows the nature of these equilibria. Figure 4 represents this graphically.

TABLE 7

EQUILIBRIA FOR THE OXIDATION OF VARIOUS SULFIDES

$$\text{Met S} + 4H_2O \rightleftharpoons \text{Met } SO_4 + 8H_+ + 8e^-$$

	E_o in millivolt	E_{pH_s} in millivolt	pH below which sulfide soluble
HgS	+ 525	+060	
Ag_2S	+ 482	+015	
Cu S	+ 436	−045	
Nis	+ 375	−110	
CoS	+ 360	−130	
PbS	+ 298	−160	
ZnS	+ 305	−170	2.07
MnS	+ 163	−310	
CaS	+ 094	−370	9.05

The outline of bacterial sulfate reduction, as established from previous experiments and from field observations, is indicated by a hatched line. The smaller, hatched area represents the values obtained in the sulfate reductions described in this paper. It may be seen at a glance that, under the conditions of our experiments, no manganese sulfide could be formed. The absence of cinnabar formation may be ascribed to the toxicity of the mercury, and we cannot account for the absence of nickel and cobalt sulfides. It should be stated that the black precipitates originating from nickel and cobalt carbonate yielded H_2S on acidification, and copious gas was formed after addition of sodium azide-iodine. Sulfides were, therefore, present. All sulfides in the diagram are acid-stable within the natural environment, sphalerite and oldhamite excepted. The use of mineral acid in the purification of sphalerite should be avoided, therefore. The region for the calcium sulfide is very small and only with intense sulfate reduction under alkaline conditions may the presence of this compound (in the absence of heavy metal) be expected. We know from practical experience that the iron sulfide (probably the hydrate) becomes soluble below a pH of 5.8. This shows that the value for troilite, as given in the literature, and as used in Figure 4, is of little use to us, as this compound probably does not occur in the aqueous environment.

Of the seven mineral species formed from fairly insoluble oxidized compounds by sulfate reduction, only the metallic silver will get a hearty welcome from all geologists. Bateman (6, p. 486) states "there are no sedimentary copper deposits free from controversy" and, according to him, "Although the arguments for a syngenetic origin are strong, there are stronger arguments that support an epigenetic origin" for the Mansfield deposits (6, p. 177, 526). Natural argentite, as stated above, is considered to be a high temperature form, stable above 179° C. We should have found acanthite in our experiments. As remarked before, the attempts to produce synthetic sulfides have been confined, for the largest part, to hydrothermal or to magmatic temperatures. It may be that a renewed attempt to obtain sulfides under "sedimentary" conditions (avoiding "outlandish" substances and acidities) will be fruitful. But the microbiologist is also at fault. It is not so long ago that the microbial world was referred to by the geologist as "carbonaceous matter." The change in attitude has been too abrupt and it should be continuously remembered that vague statements as to the prowess of microbes are almost useless. These statements should be backed up by deliberate experiments; and these experiments have, in the main, not been carried out.

The seven reductions reported upon in this paper were carried out under "unnatural" conditions: at 30° C, often with 1 percent lactate or acetate. Sometimes substances were used that are not recognized as mineral species (e.g., silver carbonate). And even if these few experiment could be repeated at lower temperatures and with more "natural" nutrients, the meager evidence presented by the authors should not be used as a convincing argument for the syngenetic origin of orebodies. There are countless common sulfides that remain unstudied, and, moreover, our negative results do not

allow of rigid interpretation. The only conclusion that can be reached is that our results probably clash with current geological concepts. We are certain that this clash is due to insufficient *experimental* evidence. It seems to us that a renewed chemical and microbiological study of the sedimentary environment is desirable. One of the chief problems confronting us is concerned with the accumulation of metals. We know that the black mud is a phosphate—and probably a uranium—trap. We have only a vague inkling about these accumulations. With the heavy metals dissipated in oceans as they are, it is their mode of concentration that remains the chief problem. Once accumulated, we are certain that the microbes will do the rest.

The experiments are being continued.

We are indebted to the late Dr. A. B. Edwards (C.S.I.R.O.), Messrs. Haddon King (Consolidated Zinc), D. O'Driscoll, W. Thomas, and, in particular, W. M. B. Roberts (all B.M.R.), for suggestions and criticism.

Bureau of Mineral Resources,
Canberra, Australia,
May 26, 1960

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GROUND-WATER CONTROL IN THE NEYVELI LIGNITE FIELD, SOUTH ARCOT DISTRICT, MADRAS STATE, INDIA

PAUL H. JONES AND V. SUBRAMANYAM

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ABSTRACT

Unconsolidated deposits of the Cuddalore series of Miocene age underlie much of the coastal plain of southern Madras. Several lignite seams occur in a thick sequence of sand, gravel, and clay that dips seaward about 40 to 100 feet per mile. The principal seam of lignite mapped in the Neyveli area averages more than 50 feet in thickness, underlies at least 80 square miles, and occurs at a minimum depth of 165 feet near Neyveli, where deposits totalling 230 million tons have been proved in an area of 4½ square miles.

The lignite seam is immediately underlain, throughout its area of occurrence, by a thick bed of sand and gravel that contains artesian water, the head of which is more than 100 feet above the top of the lignite at Neyveli. The sand and gravel aquifer is exposed to recharge in and near its outcrop area, 6 to 10 miles northwest of Neyveli, where the average annual rainfall is 41 inches.

Hydraulic tests of the aquifer indicate that ground-water control for mining by opencast from a pit 6,000 feet long and 1,200 feet wide will require continuous withdrawal of about 40,000 gallons (Imperial) per minute from wells in and adjacent to the mine. The well field, including 50 to 65 large-capacity wells, must move with the open cut; and no appreciable decrease in the withdrawal rate can be expected throughout the life of the mine, which is designed to produce about 3½ million tons of raw lignite per year.

INTRODUCTION

THE largest known deposit of fossil fuel south of the Godavari River in India occurs in the coastal belt of South Arcot District about 120 miles southwest of the city of Madras. Several seams of lignite are interbedded with un-

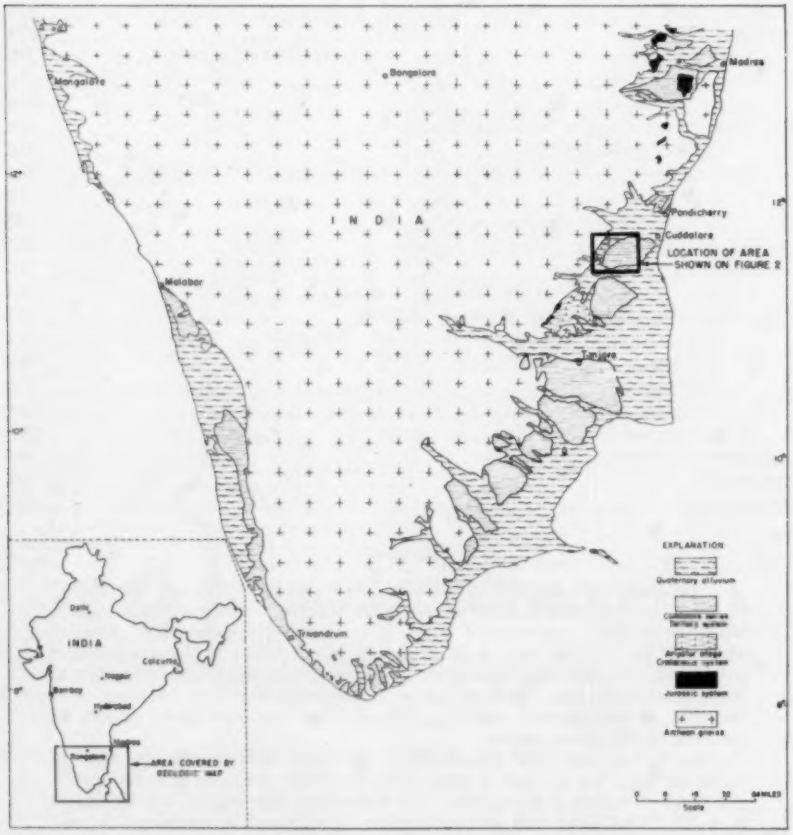


FIG. 1. Generalized geologic map of southern India showing the location of the Neyveli lignite area, South Arcot District, Madras State, India.

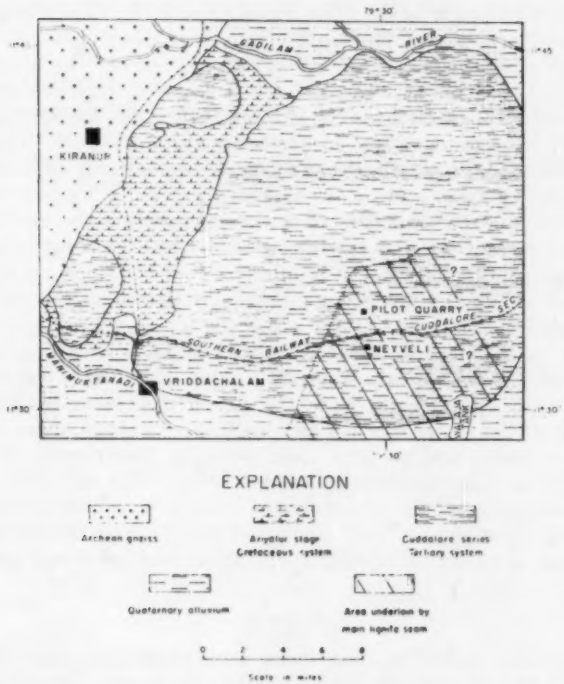


FIG. 2. Geology of the Neyveli lignite area showing the area underlain by the main lignite seam.

consolidated rocks of the Cuddalore Series of Miocene age, which underlie the coastal plain and dip gently eastward beneath the Bay of Bengal (Figs. 1, 2).

Lignite was first noted about 1930 in the borehole records of water-well drillers, and its commercial possibilities were explored in 1939 by private interests. From 1943 to 1954 exploration by Government agencies, including the Industries Department and Lignite Investigations, Government of Madras, and the Geological Survey of India, proved lignite reserves of more than 230 million tons in a proposed mining area of about 4½ square miles. The area is centered about two miles north of the village of Neyveli (lat. 11°32′N.: long. 79°29′E; Survey of India quadrangle map 58M) which is 27 miles west of the port of Cuddalore on a spur of the Southern Railway. No outcrops of lignite have been observed, and the minimum depth of occurrence of the main seam near Neyveli is about 165 feet. This seam of lignite is known to underlie an area of at least 80 square miles, although its downdip extremity has not been found.

In October 1954 investigations of the Geological Survey of India were

continued at the request of the Ministry of Production, Government of India, and its consultant, Powell-Duffryn Technical Services, Ltd., in connection with the appraisal of the feasibility of mining. Some 30 boreholes were drilled through the lignite seam, and the presence of high-pressure artesian water in sand and gravel beds immediately below the lignite was realized. Several new holes were drilled to depths of about 400 feet. Casings were set through the lignite seam in some of the wells for study of head and yield characteristics of the aquifers (water-bearing beds). Results of tests on these aquifers and study of data from flowing wells in the artesian area, a few miles to the south, led to the conclusion that the feasibility of any mining plan would depend upon the cost of effective control of ground water in the beds of sand and gravel immediately below the lignite, as the pressure head in these beds is more than 100 feet above the top of the seam at its highest point, their permeability is high, and their combined thickness in the mine area is about 170 feet. Excavation of a pilot quarry 600 feet square was halted at a depth of 150 feet to avoid the danger of flooding by floor burst.

Detailed studies of the geology and hydrology of the aquifers beneath the lignite were made, and a large-scale pumping experiment, designed by Powell-Duffryn, was undertaken between May 1955 and May 1956. A comprehensive proposal for ground-water control for opencast mining, based on results of this study, has been sanctioned and implemented by the Government of India as a part of the mining operations which are now underway.

PREFACE

Investigations leading to this report were conducted under the general supervision of G. C. Chaterji, Superintending Geologist, Ground-Water Exploration Section, Geological Survey of India, and under the immediate supervision of V. Subramanyam, then Senior Geologist and chief of the Neyveli party.

Analysis of records and basic interpretations were made by Paul H. Jones and V. Subramanyam with the valuable assistance of R. K. Sundaram. Conclusions and interpretations presented in this paper were made possible through the efforts of all personnel of the Geological Survey of India assigned to the Neyveli Project. Previous investigations, successively under the supervision of Dr. M. S. Krishnan, R. N. P. Arogyaswamy, and M. S. Balasundaram, have provided information vital to the concepts presented here.

PHYSIOGRAPHY

The Neyveli lignite field is in the coastal plain of southeastern India. The region in which it occurs may be divided into three topographic belts that converge westward towards Vriddachalam (Fig. 3). The northernmost belt is a nearly flat upland area of small relief, scrubby vegetation, and little agricultural development. It is bounded on the northwest by a northwest-facing escarpment, and on the north by plains along the Gadilam River. In places it rises more than 300 feet above sea level. Most of it is reserve

forest, although cashew-nut groves are common along its southern margin. The central belt is a gently sloping plain in which the project mine area is located. This plain slopes southeastward about 25 feet per mile, is locally dissected by streams near which the relief may be 20 to 25 feet, and is well developed agriculturally. The southern belt is a nearly flat, intensively culti-

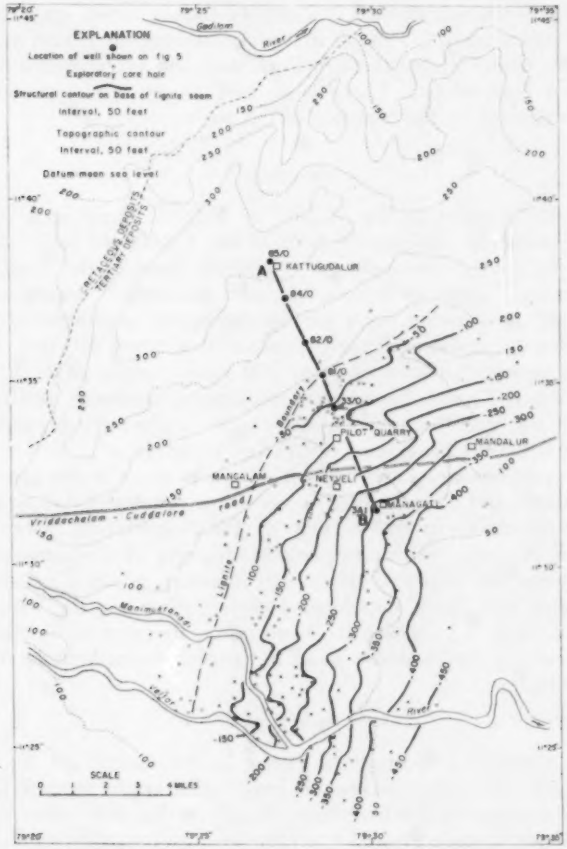


FIG. 3. Topography of the Neyveli lignite area, and altitude of the base of the main lignite seam.

vated plain along the Manimuktanadi-Vellar River system, lying south of the Cuddalore-Vriddachalam road. The relief is no more than a few feet, and the land slopes southward about 5 feet per mile.

All three topographic belts are characterized by poorly developed drainage and broad plains well preserved from erosion. The master drainage

of the region is by the Gadilam River to the north and the Vellar River to the south, both of which cross the coastal plain deposits without intercepting any significant tributaries. Although the flow of both streams is perennial, their dry-weather flow is very small.

CLIMATE

The average annual rainfall is about 41 inches, based upon 20 years of record at Vriddachalam. Most of this occurs during the period of the northeast monsoon, from October through December, and supplemental irrigation is necessary for most crops. There is no cold season, and summer temperatures are moderated by the nearness of the sea.

GEOLOGY

The lignite deposits in the vicinity of Neyveli occur in a sequence of clay, sand, sandstone, and gravel beds of the Cuddalore series of Miocene age (8, p. 515) which are believed to underlie most of the coastal plain of southeast India. Little is known of their sub-surface occurrence outside the lignite area. However, as a part of the lignite investigation, the structure and lithologic features of the deposits within about 400 feet of the land surface and beneath an area of some 200 square miles have been studied, using data obtained partly from lignite exploration boreholes, and partly from wells drilled for water supply. Many of the exploratory boreholes drilled since November 1954 have been electrically logged.

Pre-Miocene Tertiary rocks are not known to occur in the area, although calcareous sands and clays of Eocene age were penetrated below a depth of 100 feet by boreholes in the vicinity of Tularangurichchi, about 25 miles southwest of Neyveli. A narrow belt of deposits of Cretaceous limestone and marl flanks the west and northwest boundary of the Cuddalore Series (Arogyaswamy and Jacob, unpublished project maps) in the Vriddachalam-Kiranur area (Fig. 2). These are bounded on the west by Archean gneiss, which are probably the basement rocks in the plains area between Vriddachalam and Cuddalore.

Stratigraphy

Archean Gneiss.—Exposures of gneiss in the vicinity of Kiranur (lat. 11°40′N: long. 79°17′E; Survey of India quadrangle map 58M) are of interest to the ground-water investigation only in that they serve to limit the movement of water underground from the west and provide regional control of the geological structure of the more permeable deposits that overlie them. The buried topography of the gneissic rocks determines the depth of occurrence of the younger rocks and probably influenced their distribution by virtue of differential compaction over the buried ridges and valleys. There is evidence that deposition of the Tertiary rocks was controlled by the basement rock configuration in the lignite area. It is possible that Cretaceous rocks are absent beneath parts of the lignite area, as geophysical studies show a gravity high between Neyveli and Cuddalore (4, pl. 2).

Ariyalur Stage, Cretaceous System.—Between the area of gneiss and the upland area of Tertiary deposits, is a narrow lowland underlain by shell limestone, marl, and sandy shale of the Ariyalur stage of the Cretaceous system. These deposits, of marine origin, extend eastward beneath the Cuddalore series and are blanketed locally on the west by remnants of the Cuddalore.

FIG. 4. Thickness of the main lignite seam, Neyveli lignite area.

The contact between the two is unconformable, and indicates that prolonged erosion of the older terrane preceded deposition of the Cuddalore series.

The area of outcrop of rocks of the Ariyalur stage forms a lowland extending northward from Manimuktanadi River immediately west of Vriddachalam to the Gadilam River, in a belt about 16 miles long and 6 miles wide (Fig. 2). Although the exposed surface may be representative of its

ancient pre-Tertiary topography, there is good evidence that erosion since removal of the Cuddalore rocks has resulted in the creation of a drainage divide about 6 miles south of the Gadilam River, where the limestone terrane has an altitude of about 230 feet. From the divide, the land-surface slopes northward to the Gadilam River where the Ariyalur is about 110 feet above sea level at its contact with the alluvium, and southward to the Manimuktanadi River where it is about 130 feet above sea level at its contact with the alluvium. However, the relief along the contact with the overlying Tertiary rocks is in places as great as 45 feet within a mile.

The rocks of the Ariyalur stage are essentially impervious, and may be considered to form a hydraulic barrier to regional ground-water movement.

Table 1.—Mechanical analyses of formation samples of aquifers stratigraphically below third lignite seam

Depth range (feet)	Percent retained by weight (cumulative) (Screen opening in inches)								Uniformity coefficient	Effective size (inches)
	0.25	0.125	0.0937	0.0469	0.0232	0.0165	0.0098	0.0059		
Well 33/0										
240-253	—	4.19	6.34	27.55	43.07	55.65	82.53	100.0	3.1	0.007
257-267	—	—	—	0.17	12.37	49.38	83.39	100.0	2.4	0.007
293-307	—	—	10.96	29.33	55.73	71.90	86.79	100.0	5.0	0.006
323-353	1.60	13.02	16.20	37.73	63.96	78.67	90.40	100.0	5.0	0.008
Well 85/0										
98-104	—	1.74	4.47	50.44	86.51	93.94	98.26	100.0	2.8	0.49
104-114	—	8.69	13.28	52.39	82.26	92.13	97.77	100.0	3.5	0.43
118-125	0.47	2.99	4.95	24.99	58.31	77.96	93.19	100.0	3.6	0.22
125-137	—	1.88	3.78	28.66	53.75	75.46	93.55	100.0	3.2	0.26
137-145	—	15.36	22.37	53.56	77.29	87.93	96.82	100.0	4.5	0.36
145-158	—	8.76	12.80	33.85	62.34	79.18	94.14	100.0	3.6	0.28
160-182	5.78	29.73	33.95	55.61	76.54	87.71	96.86	100.0	5.6	0.35
182-190	0.61	9.86	13.36	38.74	66.01	82.83	95.67	100.0	3.7	0.31

Tertiary deposits have been removed from this belt of land at the margin of the Archean gneissic terrane, which rises to altitudes above 400 feet less than 8 miles to the west. Flood flows debouching from the gneissic terrane, also impervious to precipitation, have eroded away its mantle of Tertiary sand and gravel near the Archean contact and carried the detritus north to the Gadilam River valley, or south to the Manimuktanadi-Vellar River valley (Fig. 2).

Cuddalore Series, Tertiary System.—The rocks in which the lignite occurs range in texture from boulders through pebbles, coarse gravel, sand, silt, and clay. The deposits of gravel, sand, clay, and lignite comprise beds each ranging upwards of 70 feet in thickness that have great areal continuity.

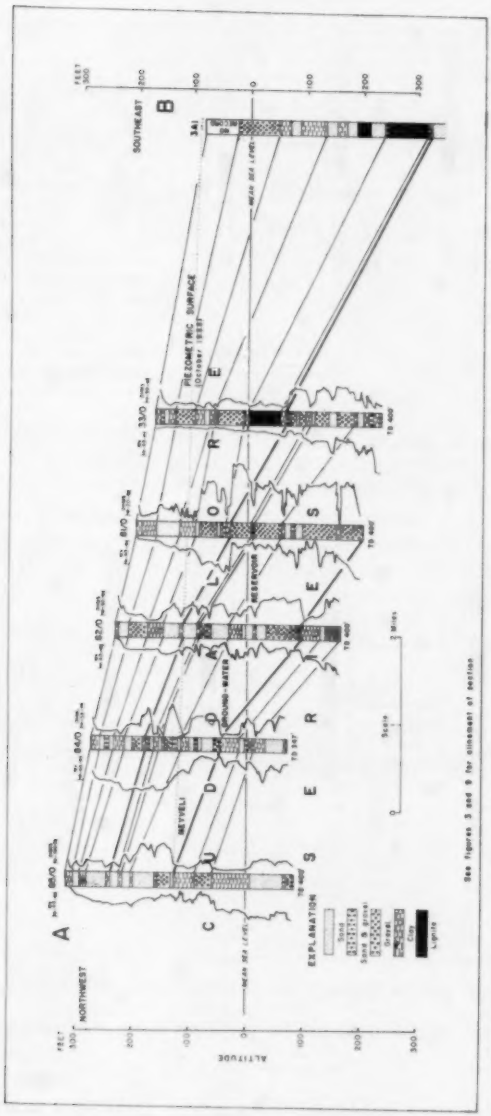
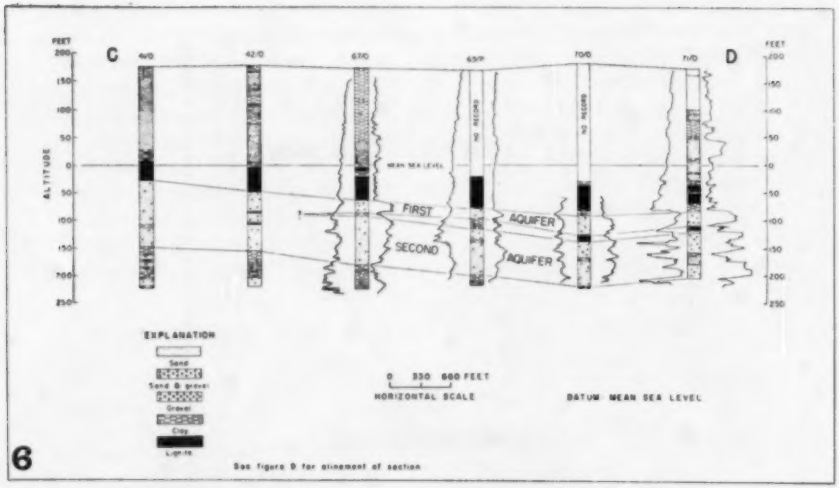


FIG. 5. Geologic section through the Neyveli area from Kattugudalur village southeastward to Managati village, along line A-B as shown on Figure 3.



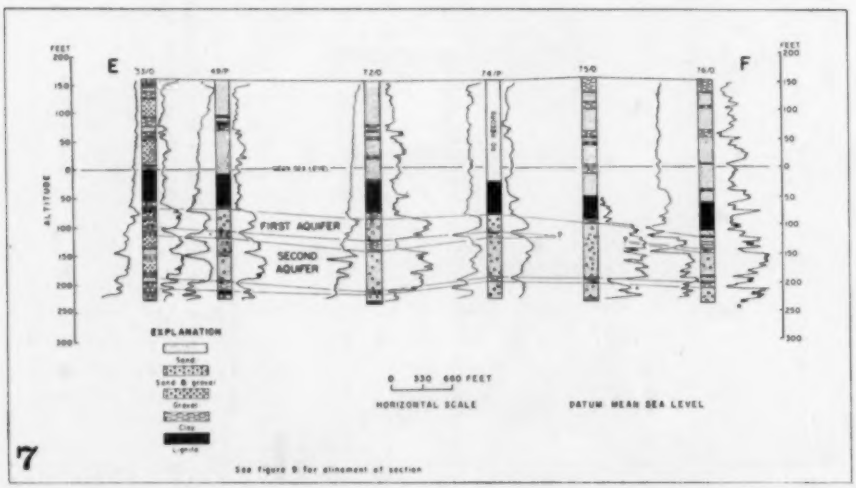


FIG. 6. Geologic section through the proposed mine area, along line C-D as shown on Figure 9.

FIG. 7. Geologic section through the proposed mine area, along line E-F as shown on Figure 9.

Their origin ranges from terrestrial to estuarine, or shallow marine, and the shore line of the Bay of Bengal appears to have crossed parts of the area of deposition many times. However, exploratory boreholes more than 1,000 feet deep penetrate no fossiliferous marine deposits near Neyveli.

TABLE 2

DEPOSITS ABOVE THE MAIN LIGNITE SEAM IN THE VICINITY OF THE PILOT QUARRY

	Thickness (feet)	Depth (feet)
Clay, sandy, light-brown	5	5
Clay, lateritic, reddish	7	12
Sandstone, clayey, mottled brown	6	18
Sandstone, hard, flaggy	2	20
Sandstone, clayey, soft gray and yellow, purple streaks	40	60
Sandstone, coarse-grained buff-colored	10	70
Sandstone, gritty with pebble lenses, soft	5	75
Clay, sandy, white to yellow	5	80
Sandstone, soft, buff-colored	1	81
Clay and sandstone, soft, yellow to brown	4	85
Sandstone, soft, light-brown	5	90
Clay, sandy, whitish	14	104
Sandstone, clayey	36	140
Clay, sandy, mottled yellow and purple	20	160
Sandstone, soft, light-yellow	7	167
Sandstone, very clayey light-gray lignitic	9	176

The lignite in the Neyveli area occurs in at least 5 seams, but only the third seam below the land surface has appreciable thickness and great areal continuity (5, Table 1 and Fig. 7). The third seam exceeds 70 feet in thickness locally and has an average thickness greater than 50 feet in the area proposed for mining. It is a dense, nonfibrous variety and contains abundant granules of amber. Its moisture content is about 50 percent in place; by dry weight, its ash content is less than 6 percent; its calorific value is about

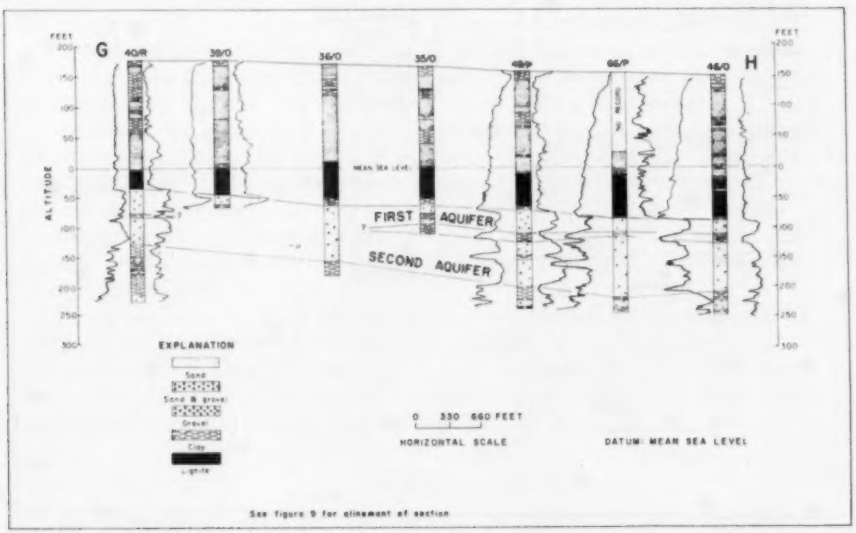


FIG. 8. Geologic section through the proposed mine area, along line G-H as shown on Figure 9.

9,000 Btu. per pound, and its volatile constituents approximate 40 percent. The third seam of lignite at Neyveli has been mapped beneath an area of 80 square miles and its downdip extremity has not been found (Figs. 3, 4).

The sand and gravel beds that immediately underlie the main lignite seam in the project mining area are areally extensive, are of moderately uniform texture, and are generally medium to coarse-grained. Table 1 shows rep-

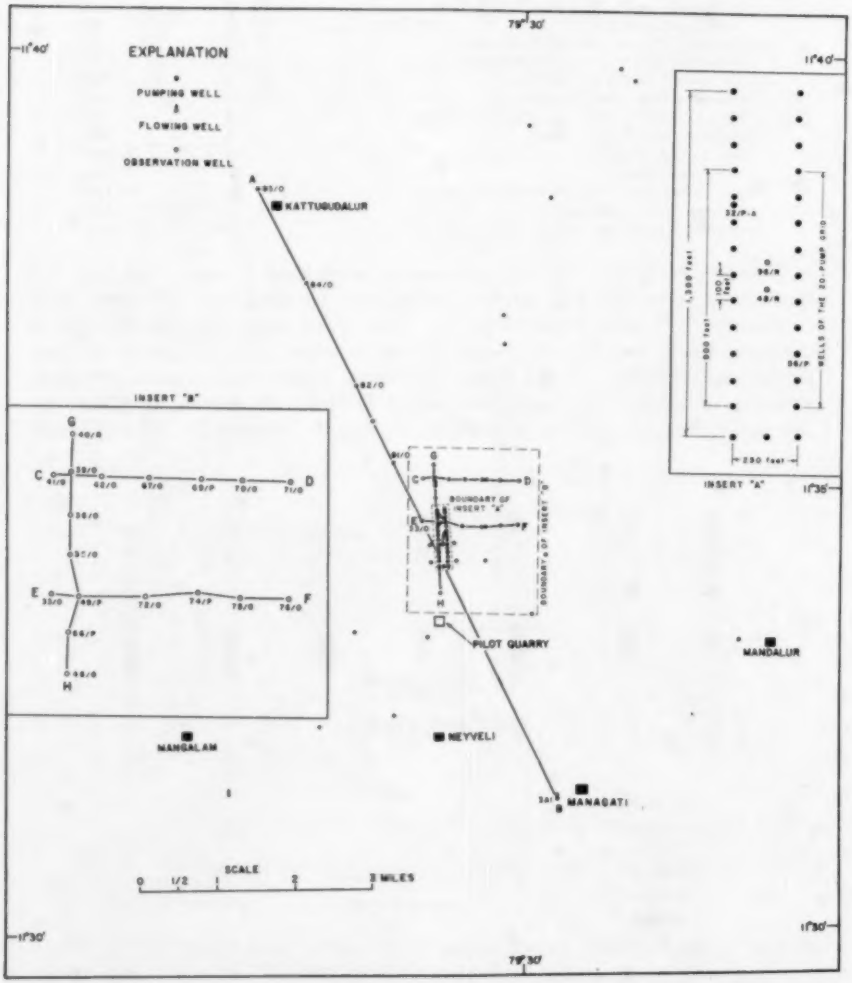


FIG. 9. Locations of pumping wells, observation wells, and geologic sections in the Neyveli lignite area.

FIG. 9a. The pilot quarry, excavated to a depth of about 150 feet.

resentative mechanical analyses of samples obtained from the mud returns during hydraulic rotary drilling. The aquifers that immediately underlie the third lignite seam occur throughout its entire mapped area of 80 square miles, and extend to the northwest of the project mine area at least 6 miles (Fig. 5). The coastwise extent of the first aquifer beneath the main lignite seam is at least 14 miles, and its extent downdip is at least 10 miles.

A bed of clay and lignite separates the first and second sand beds below the main lignite seam, but locally it is absent (Figs. 6, 7, 8, 9). The combined thickness of the sand beds therefore is of great importance to the ground-water problem.

In the vicinity of the pilot quarry (Fig. 9a), south of the site of the first open cut of the project mine, the main lignite seam is overlain by the sequence of beds described in Table 2.

In the project mine area, the thickness of overburden ranges from 160 to 250 feet, but it is generally between 180 and 220 feet. The permeability of the overburden materials is low, and their consolidation is poor. However, the lignite is known to be overlain by thick beds of highly permeable sand and gravel down the dip from the mine area.

Structure

Archean Gneiss.—The general strike of the foliation of the gneiss where it crops out in the area under investigation, is south-southwest, and the dip is southeastward. In this area, a number of basic dikes intersect the gen-

eral strike at small angles, mostly less than 30 degrees, but no faults of large displacement have been mapped. If such faults do occur in the Archean rocks, there has been no appreciable movement along them since the beginning of Miocene deposition, as no evidence of faulting has been found in the Cuddalore series.

Ariyalur Stage, Cretaceous System.—The exposure of Cretaceous rocks of Ariyalur stage in the study area is small, and its contact with the Archean and the overlying beds of Tertiary age has been carefully mapped. Individual beds in the Ariyalur stage are not exposed well enough to permit effective study of their trends. If deformation has occurred, it has not been noted, and the overlying rocks of Tertiary age do not appear to have been disturbed. The upper surface of the Ariyalur stage is an erosional surface, and where penetrated beneath the Cuddalore series, in boreholes several miles south east of its outcrop, the contact has a coastward slope of about 175 feet per mile.

Cuddalore Series, Tertiary System.—The best stratigraphic marker bed in the Cuddalore series in the area of study is the third lignite seam. In the area beneath which it has been mapped it describes a broad eastward-plunging syncline (Fig. 3). The strike in the vicinity of the pilot quarry is about N45°E, changing to N15°E at the southernmost point where it has been mapped, some 14 miles to the south. Thus its strike is an arc, and the syncline it describes opens broadly eastward. Near the mine area the dip of the top of the seam is southeastward about 40 feet per mile, steepening eastward to about 100 feet per mile. South of the mine area, the dip is southeastward about 50 feet per mile, steepening eastward to about 75 feet per mile.

Along the line of section A-B (Fig. 5) the southeastward dip of the beds of sand and gravel that underlie the main lignite seam steepens from about 50 feet per mile in the vicinity of Kattugudalur to about 80 feet per mile in the project mine area. About a mile to the southeast the dip steepens to 90 feet per mile, and this slope continues at least 4 miles. Data from flowing artesian wells about 8 miles to the south of the mine area indicate that the dip of the aquifers is about 55 feet per mile to the southeast, remaining almost constant along a dip section of 6 miles.

The maximum thickness of the Cuddalore Series along the coast of the Bay of Bengal, based upon the angles of dip, probably exceeds 2,000 feet and may be as much as 4,000 feet.

GROUND-WATER CONDITIONS

Water-Table Aquifers of the Tertiary System

The water table is the top of the zone of saturation in unconfined aquifers. In the granular rocks of the Cuddalore series it is an undulating surface that tends more to conform to the areal distribution of the rocks than to the topography of the land. As the Tertiary terrane slopes southeastward from the upland at about 25 feet per mile and the beds of the Cuddalore series dip

about 50 feet per mile in the same direction, the land surface is formed on the beveled edges of the beds. Thus, the outcrops of sand and clay tend to follow the topographic contours where the land is not deeply eroded.

The recharge area is heterogeneous in plan, comprising alternating belts of high and low surface permeability. Rain that falls on the beveled edges of the beds of clay flows over the land to the next adjacent sand-bed exposure and there sinks in. The water table formed on this terrane is a great deal more irregular than the land surface, and ranges from 20 to 100 feet below the land surface in short distances. Perched water is not uncommon, but there is little standing water in the upland area even a few hours after heavy downpours.

The pervious beds are able to transmit their recharge water downward and laterally great distances with relatively little loss of head because they have great areal continuity, and are regionally interconnected. They discharge water effectively where they are deeply eroded along the drainageways of the master streams, to the north and south.

In places distant from the major stream valleys the water table is a sequence of mounds and troughs tending to follow the strike of the geologic formations (Fig. 10). The troughs mark the trends of the outcrop areas of the more pervious beds. The axes of the troughs slope gently towards the drainageways of the master streams, and the configuration of the slopes of the water-table mounds is dominated by the adjacent troughs.

Thus the water table beneath the upland area reflects a complex system of contiguous aquifers of varying permeability, and there is no well-defined regional slope or direction of flow.

Artesian Aquifers of the Tertiary System

Artesian (confined) water is ground water that will rise in tightly cased wells above the top of the aquifer in which it occurs. Water that enters beds of sand and gravel in the Cuddalore series where they lie at or near the land surface moves down the dip and soon passes beneath and is confined by beds of clay. It then moves as in a conduit, in the direction of the hydraulic gradient to points of escape. Natural discharge occurs either through interconnections with aquifers above or below, through exposures of the pervious beds at more or less distant points of lower altitude, or slowly by percolation through the less pervious confining beds above or below.

Lithologic logs of many boreholes in the Neyveli area record extensive beds of sand, or sand and gravel, between equally extensive but generally thinner beds of clay (Figs. 5, 6, 7, 8). At least three beds of sand, ranging from about 10 to about 500 feet in thickness occur stratigraphically below the main lignite seam in the Neyveli area. Two of these, having an aggregate thickness of about 110 feet, underlie the projected mine area and are known locally as the "first" and "second" aquifers. The "third" aquifer, which is the thickest of the three, is fortunately separated from the second aquifer in the mine area by an extensive bed of hard clay generally about 60 feet thick. These three artesian aquifers comprise a single regional hydraulic unit; they

have approximately the same head conditions in the vicinity of the projected mine, and are therefore grouped together as the Neyveli ground-water reservoir (Fig. 5).

Recharge.—Toward the north and west, where the Neyveli ground-water reservoir receives recharge, its aquifers occur at or near the land surface and contain unconfined water. They dip less steply and their deposits are coarser textured in these areas than farther downdip. Along the line of section A-B (Fig. 5) they are locally interconnected, although this is not evident from the records of wells shown. Their combined thickness increases rapidly with distance down the dip so that they are readily able to transmit water from the area of outcrop.

The water-level map (Fig. 10) indicates that the head of water in the Neyveli ground-water reservoir is not much greater than 120 feet above sea level. It also shows that the area of highest water level underlies and transversely intercepts a deep trough in the water table, the bottom of which also lies at an altitude of about 120 feet. This water-table trough, which extends north-northeast of well 81/0 more than 4 miles, has a pronounced effect on the distribution of head in the Neyveli ground-water reservoir, to both the northeast and southwest of its intersection with the 120-foot contour. The nearly east-west trend of the ground-water divide of the confined reservoir between the 120-foot contours, passing a short distance north of well 85/0, suggests that downward seepage from the water-table aquifer into the Neyveli ground-water reservoir is very great along this line. In spite of this, the water table rises more than 120 feet in 3 miles, westward along the axis of the ground-water divide, probably owing to a progressive thickening of less permeable deposits above the artesian aquifers of the reservoir, as well as to a thinning of the permeable beds.

This ground-water divide is the northern boundary of effective recharge to the Neyveli ground-water reservoir where it lies beneath the lignite area. All water that enters the reservoir north of the divide moves toward the drainage area of the Gadilam River. However, as ground-water withdrawals increase in the vicinity of the projected mine, through water-control measures or for public or industrial water supplies, the ground-water divide will shift northward. As a consequence, a larger proportion of available recharge will be diverted southward, reducing the rate of decline of ground-water levels that the pumping otherwise might be expected to cause, and decreasing the rejected recharge now occurring as effluent seepage along the Gadilam River.

A notable feature of the piezometric contours north of the ground-water divide is a broad "plateau," which stands more than 105 feet above sea level northward for a distance of nearly four miles. Thus a decline of about 15 feet in the altitude of the ground-water divide as a consequence of heavy withdrawals in the Neyveli mine area would shift the divide northward about four miles, increasing the effective area of recharge to the aquifers beneath the vicinity of the mine by at least 30 square miles. Although the effect of this cannot be evaluated quantitatively at this time, it is a further indication that water control by pumping will not be an easy matter.

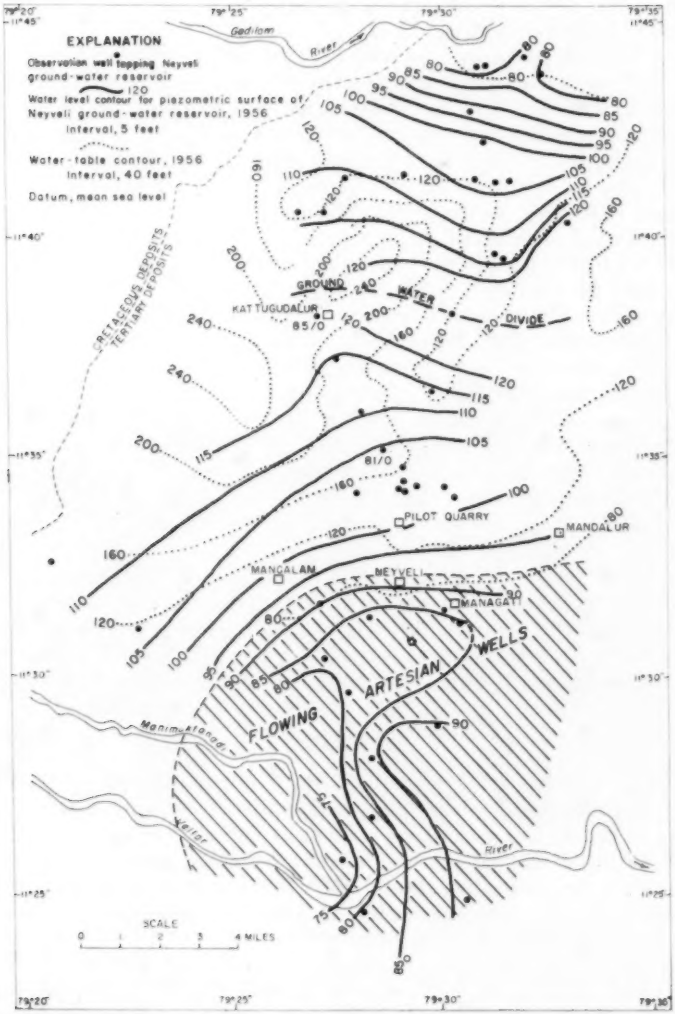


FIG. 10. The relation of the water table to the piezometric surface of the Neyveli ground-water reservoir.

Movement.—The most significant features of ground-water movement in the Neyveli ground-water reservoir are: regional hydraulic continuity; gentle hydraulic gradients; divergent flow from the low ground-water divide about 6 miles north of the pilot quarry; and converging flow south of Neyveli,

in the Vellar River lowland, as a consequence of large, continuous withdrawals from flowing artesian wells.

The regional hydraulic continuity of flow in the Neyveli ground-water reservoir is indicated by the single piezometric surface of water in the several aquifers, as evidenced by general agreement of water levels in widely spaced wells which tap different aquifers within the reservoir. Furthermore, the northward spread of the cone of pressure relief during the large-scale demonstration test, as shown on Figure 12, could occur only under conditions of hydraulic continuity, as the stratigraphic equivalents of the aquifers tapped by the pumped wells stand 20 to 90 feet above the piezometric surface in well 84/0 (Fig. 5), where a water-level decline of about 2 feet was observed in the third (lowermost) aquifer of the reservoir.

The gentle hydraulic gradients in the Neyveli ground-water reservoir could indicate that the rates of regional flow in it are small, if its ability to transmit water is small. However, the coarse texture and lack of consolidation of the beds that comprise the aquifers, together with their considerable cumulative thickness, suggest that they have a high transmissibility. Aquifers in the reservoir distribute recharge from the overlying water-table aquifers almost as rapidly as it arrives. Although the regional gradient steepens locally in the area of flowing wells, it is nowhere more than 10 feet per mile, which is moderate under the existing conditions of withdrawal from irrigation wells.

Large volumes of water are moving northward from the regional divide in the Neyveli ground-water reservoir into the Gadilam River, whose channel is nearly parallel to that of the Vellar River, and whose gradient is nearly the same. However, the ground-water divide is more than 3 miles north of the center of the interfluvial area, and this may be the consequence of large continuing withdrawals from the 140 flowing wells along the Vellar River (Figs. 10 and 11). Prior to the construction of these wells the divide may have been much closer to the center of the interfluvial area.

Beneath an area of at least 100 square miles, bisected by the Vellar River, ground-water converges upon the area of flowing artesian wells. Closure of the 90-foot water-level contour is indicated (Fig. 10), and there can be no doubt that the former seaward hydraulic gradient has been reversed in the area extending several miles to the east of the flowing wells.

Discharge.—All discharge rates and values of transmissibility given in this report are expressed in Imperial gallons.

The cumulative rate of flow of about 140 drilled artesian irrigation wells in the broad valley of the Vellar River is about 21,000 gallons per minute, approximately 30 million gallons a day (11, p. 2). Although variations in this withdrawal rate occur seasonally with change of water level in the recharge area, near-equilibrium conditions of flow and head appear to have been established, and no appreciable continuing decline of head is evident.

Two large-scale demonstration pumping tests were conducted by the Neyveli Lignite Investigation Project, one between late February and early June 1956, and the second about one year later, for appraisal of the feasibility of heavy pumping from wells as a means of ground-water control for mining.

During the second test, in the spring of 1957, a field of 29 closely spaced large-capacity wells tapping the first and second aquifers pumped continuously for more than a month at a maximum rate of about 24,500 gallons of water per minute (Fig. 9). Industrial and public-supply wells of the Neyveli Lignite Corp. in the project mine area had a continuous discharge of about 1½ million gallons a day during this period.

Water discharges continuously from the Neyveli ground-water reservoir into overlying, and perhaps also underlying, aquifers, and through natural outlets where the aquifers are intersected by scour trenches of the master streams.

Hydraulic Tests.—Quantitative study of ground-water movement in an aquifer is possible only after its hydraulic characteristics have been deter-

FIG. 11. Flowing well tapping the first aquifer beneath the main lignite seam about 3 miles southeast of Neyveli.

mined. If these are known, it is possible to predict the decline of head that will occur in an aquifer at any given distance from one or more pumping wells that tap it, if the rate and duration of pumping of the wells are known. If a granular aquifer (a saturated bed of sand or gravel) is reasonably homogeneous and isotropic in texture, is areally continuous for a few square miles, and has about the same thickness throughout this area, the computed values of water-level drawdown or recovery with time will be close enough to measured values to provide a sound basis for engineering design. Aquifers in the Neyveli ground-water reservoir satisfy these requirements very well.

The hydraulic characteristics of an aquifer are its transmissibility and its storage coefficient. Transmissibility is the product of the permeability and

the thickness of an aquifer, and may be defined as the gallons per day that will pass through a cross section of an aquifer 1 mile wide, and the full saturated thickness of the aquifer, under a hydraulic gradient of 1 foot per mile. The coefficient of storage of an aquifer may be defined as the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface.

The hydraulic characteristics of an aquifer can be determined in a number of different ways, but the most satisfactory method in current use is the discharging-well method. This requires only that one or more wells be pumped for specified times at known constant rates sufficient to cause appreciable change of water level (preferably at least a few feet) in one or more observation wells tapping the same aquifer at known distances from the pumped well or wells. The time rate of change of water level in the pumped wells and observation wells may be analyzed using the Theis non-equilibrium formula (12), for the period of drawdown, recovery, or both. The result of a change in pumping rate, either an increase or a decrease, may be analyzed similarly. This method is commonly referred to as a pumping test, sometimes as an aquifer test.

The first such test, of the second aquifer below the lignite in the Neyveli ground-water reservoir, was made in April 1955 (10) using two small-capacity drilled wells about 330 feet deep at the ends of a row of 6 wells immediately north of the pilot quarry. First the well at the east end was pumped at a rate of about 330 gpm, and changes of water level were observed in the other 5 wells; and after levels had recovered, the well near the west end of the line of wells was pumped, and changes of water level observed. Analysis of the water-level data by the Theis method gave remarkably consistent values for T (transmissibility) and S (storage coefficient). The average values obtained were $T = 120{,}000$ gpd per foot, and $S = 1.77 \times 10^{-4}$.

Similar tests to determine the hydraulic characteristics of the first aquifer below the main lignite seam were recommended at that time, but were not made owing to the initiation of the large-scale demonstration test by the mining consultant.

Hydraulic tests using wells that tap both the first and second aquifers in the grid were made February 22, 23, and 25, 1956 and combined-aquifer characteristics were computed from the data obtained. Based upon records from 5 observation wells in widely different directions, and at distances ranging up to 3,300 feet from pumped well 32/P-A, T values ranged from about 80,000 to 170,000 gpd/ft, and S from about 1.8×10^{-4} to 2.5×10^{-2}. Records from 7 observation wells similarly spaced with respect to pumped well 56/P gave values of T ranging from about 60,000 to 220,000 gpd/ft and S from about 1.7×10^{-4} to 4.5×10^{-4}. The wide range of these values is explained by the geological conditions, as the first and second aquifers thicken appreciably in the directions of increasing T, and are actually joined in two directions from the pumping wells (Figs. 6, 7, 8). Review of combined-aquifer characteristics in the light of geological information leads to

estimated average values for T and S applicable to the well field. These values are, $T = 140{,}000$ gpd/ft and $S = 3 \times 10^{-4}$,

A large-scale demonstration test was made in the area proposed for mining, using, in the first stage, 20 large-diameter (18 inch) wells 400 feet deep cased with slotted pipe, and gravel packed through all or part of the first and second aquifers. The wells were drilled in two parallel rows, each row consisting of 10 wells 100 feet apart, the rows being 250 feet apart (Fig. 9). The design capacity of these wells was 1,000 gpm each, and the theoretical capacity of the well field was 20,000 gpm. The Ministry of Production, Government of India, hoped to achieve a 200-foot decline of water level in the first and second aquifers in this test. About 30 small-diameter observation wells were installed in rows extending from the grid.

The altitude of the land surface in the demonstration well field is about 160 feet above sea level. The piezometric surface was about 60 feet below the land surface, or 100 feet above sea level. The base of the main lignite seam is about 240 feet below the land surface, or about 80 feet below sea level. Therefore, a 200-foot decline of head in the first and second aquifers beneath the lignite would result in establishment of water-table conditions in the first aquifer, the water table being about 20 feet below the base of the lignite (Figs. 5, 6, 7, 8).

To effect the desired 200-foot decline of head in the first and second aquifers beneath the demonstration well field, partial dewatering of the first aquifer is necessary. The volume of water to be removed from water-table storage in the upper part of the first aquifer is a function of the size and shape of the dewatered zone, and its specific yield.

The geometry of the inverted cone of dewatered material to be developed in the first aquifer was analyzed on the basis of the combined hydraulic characteristics of the first and second aquifers, as all wells in the pumping grid were constructed to tap both aquifers. The equilibrium slope of the cone of depression about the pumping grid when the desired dewatering of the first aquifer is accomplished will result in complete saturation of the first aquifer (artesian conditions) outside the circle, or ellipse, described by the intersection of the piezometric surface of the second aquifer and the top of the first aquifer. On the basis of this concept, the dimensions of the inverted truncated cone of dewatered material in the first aquifer may be computed. The mean thickness of the inverted truncated cone is 20 feet; the lower mean radius of the cone is 500 feet; and the upper mean radius is 1,900 feet. Because the drawdown of water level varies inversely with the logarithm of distance, the approximate volume of the dewatered part of the first aquifer may be computed for a cylinder of sand having a mean radius of 1,200 feet.

The volume of the truncated cone of material in the first aquifer is about 90 million cubic feet. The average porosity of disturbed formation samples of the first aquifer is 27.5 percent. If the specific yield averages 20 percent, then some 18 million cubic feet of water must be removed from storage to achieve the desired dewatering.

To develop the equilibrium cone of depression described above, in both first and second aquifers, and to drain the zone to be dewatered in the first

aquifer, an extended period of pumping from wells would be required. If the grid of pumping wells can be assumed to act as one well, with a radius of 500 feet, and the period of pumping is set at 30 days, then the average withdrawal rate required to lower the head as desired would be about 25,100 gallons per minute. To drain the zone to be dewatered in the first aquifer in this same period, an average withdrawal rate of about 2,600 gallons per minute would be required. The total average pumping rate required to accomplish the lowering of water level and dewatering of the first aquifer in a 30 day period would thus be about 27,700 gallons per minute.

Under actual conditions, at this average rate of withdrawal, the water level will decline about 180 feet very rapidly, probably within 48 hours, to the top of the first aquifer in the vicinity of the demonstration well field. The remaining decline of 20 feet will occur slowly during the next 28 days. After the required depth of dewatering has occurred, the withdrawal rate required to maintain this condition will decrease as the inverse logarithm of time to a constant minimum rate of about 25,000 gallons per minute. A report summarizing this analysis was made available to the Lignite Project Coordinating Committee, Ministry of Production, Government of India in April 1956 (Geological Survey of India, 1956).

Pumping from the demonstration well field was stopped early in April. The maximum sustained withdrawal rate from all 20 wells was only about 15,000 gpm, and averaged only about 14,000 gpm, because of well and pump failures. However, the cone of depression developed by this withdrawal over a period of 63 days spread more than 5 miles from the center of the well field, caused a maximum decline of about 180 feet in one well at the center of the well field, and a decline of nearly 3 feet in well 84/0 at a distance of 4 miles (Figs. 12, 13). The time-drawdown curve of water level in well 48/R (at the geometrical center of the well field) demonstrates that, while under artesian conditions, the head in the aquifer adjusts quickly to any change in the rate of withdrawal, and continuation of pumping at a constant rate thereafter results in no appreciable continuing decline of water level (Fig. 13).

To increase the rate of sustained withdrawal sufficiently to accomplish the desired 200-foot decline of head, 9 additional wells of 1,000 gpm capacity were installed at the ends of the existing well field, although their effectiveness would have been greater if they had been drilled within the perimeter of the existing well field. The length of the well field was increased to 1,300 feet and the maximum sustained rate of withdrawal, 24,500 gpm, caused the head to decline more than 200 feet in only one observation well, 96/R, which tapped the second aquifer only (Fig. 14). It is not likely that the head declined below the top of the first aquifer at any point, as very few of the pumped wells effectively tapped the first aquifer. However, the practicability of lowering the head of water in the aquifers below the main lignite seam by heavy, continuing withdrawals from wells was demonstrated to the satisfaction of the Government of India, and the feasibility of ground-water control for mining was accepted.

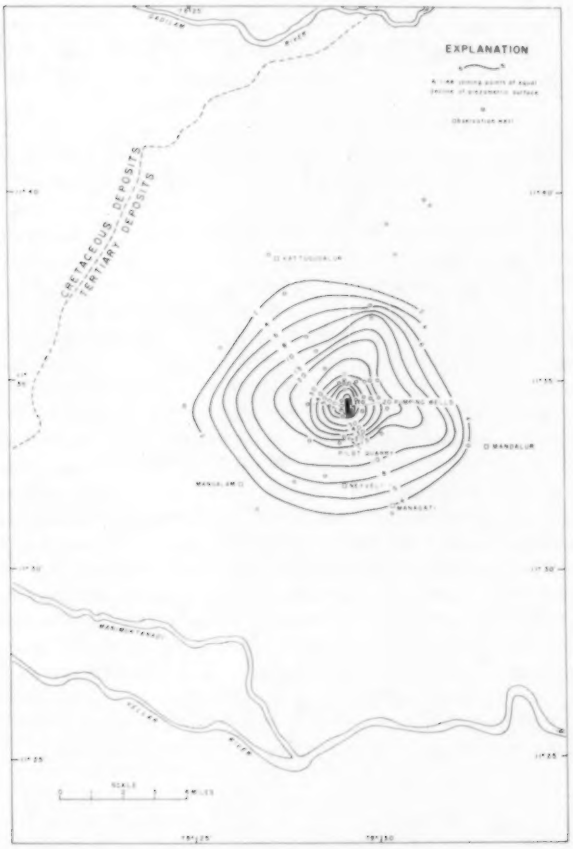


FIG. 12. Decline of the piezometric surface of the Neyveli ground-water reservoir after 63 days of pumping at an average rate of about 14,000 gallons per minute (Imperial).

Quality of Water.—The chemical quality of water from the first and second aquifers in the Neyveli ground-water reservoir, according to the meager available information, is excellent for irrigation purposes and very good, after low-cost treatment, for domestic and most industrial uses. The content of dissolved solids is generally less than 250 ppm; the chloride (Cl) content less than 20 ppm; and the iron (Fe) content very low. However, the total hardness is generally between 150 and 250 ppm. The silica (SiO_2) content averages about 100 ppm, which is far too great for use in the high-pressure steam boilers of a planned thermal power plant. The water may be slightly corrosive as it comes from the wells, as the pH ranges as low as

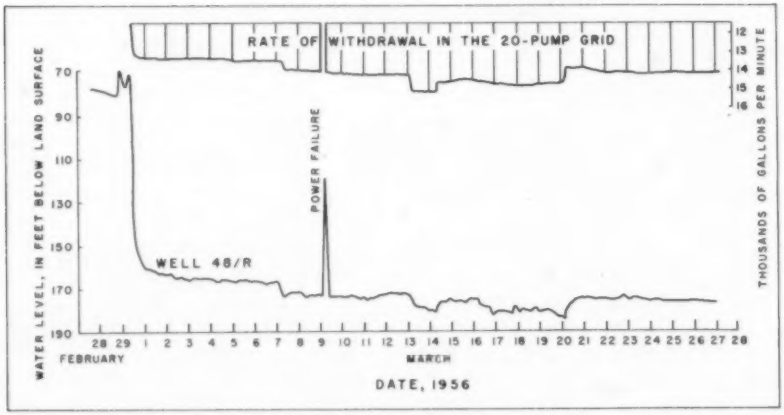


FIG. 13. Graphs showing the relation of the water level in well 48/R to the rate of withdrawal in the 20-pump grid.

6.2. There is a small amount of dissolved hydrogen sulfide (H_2S) gas, which immediately leaves the water on aeration.

The physical quality of the water is ideal for all uses, as it is clear and colorless, and, after aeration, odorless. Turbidity in some samples is believed to be due to poor well construction or incomplete development, and should be no problem. The temperature ranges from 82° to 84°F, the cooler water coming from the first aquifer. The temperature of water from any well tapping a single aquifer in the mine area or industrial area will be relatively constant with time, and this is a very important consideration for chemical-plant use, because of the range of air temperatures at Neyveli.

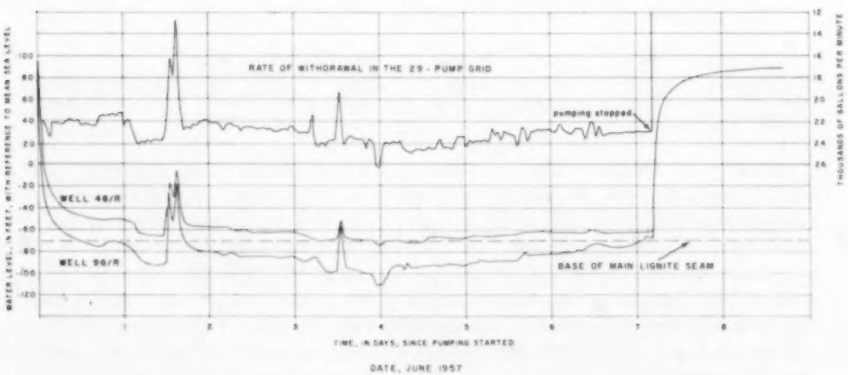

RATE OF WITHDRAWAL IN THE 29 - PUMP GRID
pumping stopped
WELL 48/R
WELL 96/R
BASE OF MAIN LIGNITE SEAM
TIME, IN DAYS, SINCE PUMPING STARTED
DATE, JUNE 1957

FIG. 14. Graphs showing the relation of water levels in wells 48/R and 96/R to the rate of withdrawal in the 29-pump grid.

GROUND-WATER CONTROL FOR MINING

The Neyveli Lignite Corp. proposes to lower the head of water in both the first and second aquifers below the lignite. This will require the installation of some 65 large-diameter (probably 18-inches or larger) wells about 380 feet deep, equipped with pumps of 1,000-gpm capacity, in the immediate vicinity of the mine cut, which will be about 1,200 feet wide and 6,000 feet long. Although the best methods for drilling and constructing the wells have not been decided, experiments designed to settle this question are now in progress. The average rate of withdrawal for the first 30 days is computed, on the basis of the assumed average values of T and S, to be about 50,000 gpm, to lower the head of water about 200 feet (20 feet below the base of the lignite seam) and dewater the upper part of the first aquifer where it is intercepted by the inverted cone of depression. After the first 30 days the pumping rate can be reduced to about 40,000 gpm, but this must continue during the entire working life of the mine. No appreciable reduction of the withdrawal rate will occur with time, by virtue of the factors discussed above under Recharge, Movement, and Discharge. As the mine cut moves into areas where the base of the lignite seam occurs at greater depth, a proportionate increase in the sustained rate of withdrawal will be necessary.

At an annual mine output of 3½ million tons of raw lignite, the cost of ground-water control by pumping is estimated by the mining consultant to be about Rs. 1.6 (about $0.34) per ton. This includes provision for three alternative sources of electric power for the well pumps, necessary in view of the disastrous consequences of even a short-term (1-day) cessation of pumping.

SUMMARY

The results of geologic and hydrologic studies in the Neyveli lignite area confirm the practicability of mining the main seam by opencast in an area of 4½ square miles immediately north of the Cuddalore-Vriddachalam spur of the Southern Railway at Neyveli station. Hydraulic tests indicate that the head of ground water in the first and second aquifers below the main seam can be effectively and economically controlled by means of a battery of pumped wells in or near the mine cut.

U. S. Geological Survey,
Idaho Falls, Idaho,
Geological Survey of India,
Calcutta,
June 10, 1960

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GEOLOGY OF THE TEMISCAMIE IRON-FORMATION, LAKE ALBANEL IRON RANGE, MISTASSINI TERRITORY, QUEBEC, CANADA

TERENCE T. QUIRKE, JR.

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ABSTRACT

The Lake Albanel iron range is located 400 miles north of Montreal, Quebec. Exploration has been conducted in the area for iron ore since 1953. Sediments of the Mistassini group, which include the Temiscamie iron-formation, lie unconformably on older granites and on the southeast have been brought into juxtaposition with rocks of the Grenville metamorphic complex along the Mistassini fault (Grenville fault).

The Temiscamie iron-formation has been divided into six members: lower argillite, lower sideritic chert, magnetitic chert, upper argillite, magnetitic iron-silicate and upper sideritic chert. These members are described in detail. Ten new chemical analyses of iron-formation are presented.

The structure of much of the iron range is simple but increases in complexity near the Mistassini fault. In general the paragenesis of the minerals is simple. Siderite, chert and hematite formed first along with, or shortly followed by stilpnomelane, minnesotaite and octahedral magnetite.

INTRODUCTION

THE Lake Albanel iron range is located approximately 100 air miles north of Chibougamau, Quebec, and 400 miles north of Montreal (Fig. 1). The

nearest rail head is at Chibougamau, but an all-weather road extends to within 70 miles of the southern end of the range.

Recent exploration by Albanel Minerals Ltd. has made possible a detailed study of the Temiscamie iron-formation, one of several such iron-formations currently being investigated as a source of iron ore. By the end of 1957 besides geologic mapping, geophysical surveying and trenching, over 30,000 feet of diamond drilling had been done in the area. This information was

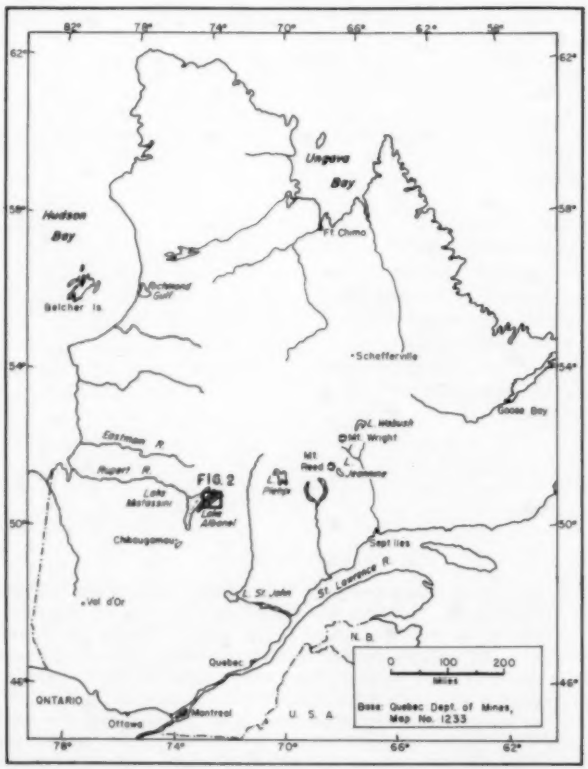

FIG. 1. Index map of Quebec showing the location of the Lake Albanel iron range and Figure 2.

used in conjunction with laboratory studies in preparing a Ph.D. dissertation at the University of Minnesota (14), of which this paper is a part. By the end of 1959, over 60,000 feet of diamond drilling and more detailed geologic mapping had been completed. Nine ore bodies of magnetic iron-formation have been explored and a minimum of 200,000,000 long tons of desirable magnetite concentrates containing 66.08 percent iron and 7.72 percent silica will be available.

A review of the literature and previous work in the area is available elsewhere (14, 15). The glacial geology is treated in some detail by Neilson (9, 12). As is normal in this part of the Canadian Shield, glacial deposits cover most of the "critical" areas and generally complicate interpretation of the bed-rock geology even in areas of otherwise straightforward structure or stratigraphy. Glacial deposits will not be discussed further.

ACKNOWLEDGMENTS

The field work was done during the summers of 1956, 1957 and 1959 while the writer was employed by Albanel Minerals Ltd. The views and knowledge of the other geologists of the company, particularly J. T. Neal and W. R. Sutton, have aided and stimulated the writing of this paper. Much of the chemical analysis of the iron-formation was done by the Cleveland-Cliffs Iron Co. The company also generously supported the research during the academic year of 1957–58 at the University of Minnesota.

Special mention is due J. W. Gruner who not only made many helpful suggestions during the preparation of the thesis but who also critically read the manuscript of the present paper. H. L. James also generously offered several suggestions and clarifications particularly in regard to the discussions of facies of iron-formations. It is a pleasure to acknowledge the helpful discussions, cooperation and valuable assistance received from M. W. Bartley, General Manager, Albanel Minerals Ltd., B. H. Boyum, Chief Geologist, Cleveland-Cliffs Iron Co., J. M. Neilson, Michigan College of Mining and Technology, and F. D. Holland, Jr., University of North Dakota.

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REGIONAL GEOLOGY

The regional geology has been treated in some detail by Quirke et al. (15). This is summarized here (see also Table 1).

The schistose volcanics and meta-sediments of the Sam Gunner group are the oldest rocks of the region. They lie ten miles to the north of the map area (Fig. 2), strike nearly east-west and have essentially a vertical dip. The Takwa intrusive complex intrudes the Sam Gunner group on the north, west and south. This complex consists of granites and granite gneisses in which are found inclusions of, and are contaminated by, rocks of the Sam Gunner group. Lying unconformably on rocks of the Takwa complex along its western margin are relatively unmetamorphosed conglomerate, sandstone and graywacke. This sequence of sediments comprise the Papaskwasati group and crop out mainly in an area between the Papaskwasati River and the Takwa Mountains about five miles north of Lake Mistassini. The Papaskwasati group is considered by Neilson (11, p. 6) to be conformably overlain by rocks of the Mistassini group.

Rocks of the Mistassini group lie within the basin partially occupied by

TABLE 1

TABLE OF FORMATIONS

Pleistocene and Recent			
UNCONFORMITY			
PRECAMBRIAN	Grenville metamorphic complex		Granites and associated intrusives Orthogneiss Paragneiss
			Coom Lake intrusions
	Mistassini group	Kallio formation	Slate, arkose, graywacke
		Temiscamie iron-formation	Upper sideritic chert member
			Magnetitic iron-silicate member
			Upper argillite member
			Magnetitic chert member
			Lower sideritic chert member
			Lower argillite member
		Boulder Bay formation	Quartzite
		Local(?) Unconformity	
		Upper Albanel formation	Dolomite
		Lower Albanel formation	Dolomite
	Papaskwasati group		Quartz sandstone, pebble conglomerate
	UNCONFORMITY		
	Takwa intrusive complex		Granite and related intrusions Gneiss
	INTRUSIVE CONTACT		
	Sam Gunner group		Interbedded sedimentary and volcanic rocks

Lake Mistassini and Lake Albanel. They are represented by dolomite, quartzite, iron-formation, slate and graywacke. The Mistassini group is terminated to the southeast by the Mistassini fault zone, part of what is otherwise termed the Grenville fault or Grenville Front. Southeast of this fault zone lies the Grenville metamorphic complex of paragneiss, orthogneiss, granite, and associated intrusions. Near Coom Lake between the Temiscamie River and Lake Albanel, diorite and metadiorite intrude sediments of the Mistassini group. The age of the Coom Lake intrusions relative to the Grenville complex has not been determined.

STRATIGRAPHY OF THE MISTASSINI GROUP

Lower and Upper Albanel Formations

Wahl (17) and Neilson (9, 12) described these formations in some detail. In general they consist of dolomite, dolomitic sandstone and argillaceous dolomite colored various shades of gray. Fossil cryptozoa or algae with associated anthraxolite are found in the upper part of the Upper Albanel formation. The total thickness of the dolomite is estimated by Neilson (9, p. 50–51) to be between 6,500 and 8,400 feet.

Boulder Bay Formation

Because of its narrow outcrop width the Boulder Bay formation is included on the geologic map (Fig. 2) with the Temiscamie iron-formation.

Areal Distribution.—Outcrops of Boulder Bay quartzite are virtually continuous from Canso Bay to Kapotagen Bay overlying the Upper Albanel dolomite. Wherever diamond drilling is sufficiently deep this quartzite always is found below the lowest member of the Temiscamie iron-formation.

Lithology.—The quartzite is vitreous white or light gray in outcrop and generally contains more than 90 percent of rounded quartz grains ranging in size from 1.0 mm to less than 0.3 mm in diameter, averaging about 0.4 mm. Impurities consist of chlorite, iron carbonate and minor amounts of chert in the matrix. Small grains of plagioclase and zircon are sparse. At the north and south ends of the range the quartzite is less pure: the quartz content is as low as 30 percent, the grains are sub-rounded to angular, the amount of carbonate and chlorite concomitantly increase.

Thickness.—The formation along the lake front measured from drill core and in outcrop is generally between 30 to 50 feet thick. However, at the south end of the range it is as thin as seven feet, but to the northeast between Coom Lake and the Temiscamie River it is over 100 feet thick.

Relations to Underlying and Overlying Rocks.—The contact of the Boulder Bay quartzite with the underlying Albanel dolomite in some places is a thin (less than ½ inch) undulating limonitic zone and in other places is marked by boulders of dolomite up to five feet in diameter, in a matrix of quartzite. Where boulders are absent, the zone between the two formations was not seen to cut any bedding of the dolomite, nor was any angular unconformity seen even where boulders were present in the quartzite. The unconformity between these two formations is considered to be only local in nature.

The contact with the overlying Temiscamie iron-formation may be either disconformable, conformable or gradational. Disconformable relations were seen in one outcrop northeast of Kallio Lake where the lower member of the iron-formation rests on an irregular surface of white quartzite. Most of the contacts observed from drill core seem to be conformable. As seen in outcrops at the north end of the range northeast of Plateau Lake, south of Coom Lake and along Lake Albanel, the contact is gradational. Towards the top of the formation the quartz grains become smaller and less abundant, and the relative amount of chlorite and carbonate matrix increases. The rock becomes dark green and does not fracture through the quartz grains but around them. Where quartz grains are no longer noticeable and where the rock becomes banded the lower member of the Temiscamie iron-formation begins. Interbedding of the two formations also occurs in some places.

Temiscamie Iron-formation

Detailed mapping along with information from diamond drill holes and laboratory studies has warranted the division of the Temiscamie iron-formation into six members. Unfortunately, it is impossible to show the member

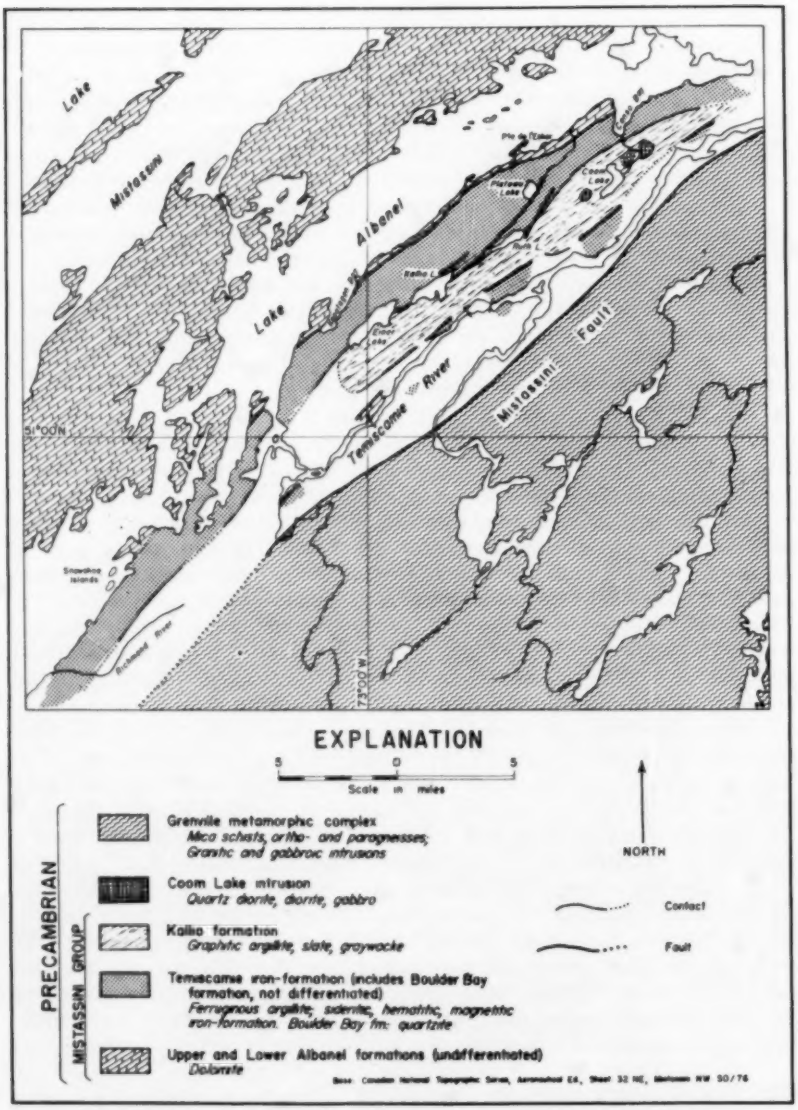

FIG. 2. Geologic map of the Lake Albanel iron range. White areas are those of little or no outcrop. Geology compiled from sources given in text.

boundaries on the accompanying geologic map (Fig. 2) because of its small scale.

Lower Argillite Member.—This member is found everywhere at the bottom of the Temiscamie iron-formation. Because of its lack of resistance to weathering it was seldom seen on the surface, but it was encountered in every hole drilled to sufficient depth.

In outcrop the argillite is dense black, but it may show stains from the weathering of pyrite. Although bedding, including cross-bedding, can be seen distinctly in some outcrops, on joint surfaces it appears massive. Secondary cleavage is absent but bedding parting, along which graphite is concentrated, is conspicuous.

Fine-grained muscovite, minnesotaite and other layered silicates such as biotite comprise as much as 90 percent of the rock. Light-green chlorite is also common and occurs as small lenses and irregular scattered flakes. Dust-size graphite occurs throughout the member. It may be scattered, concentrated in thin lenses or in persistent thin layers.

Small (less than 0.03 mm) angular grains of quartz are in places scattered through the rock, but do not exceed five percent. Plagioclase grains also occur, but less commonly. Chlorite occurs with both. Euhedral pyrite, magnetite and stilphomelane are sparse.

Analysis B of Table 2 gives the composition of a specimen of core from this member along with several other analyses of somewhat similar rocks. Although the analysis was made on only four inches of core, it is thought to be fairly representative of the member as a whole based on the comparison of a thin section from this rock and many thin sections of other specimens from the member. The member is made up of thin (less than 5 mm) beds that may differ markedly in composition; however, as a whole the member seems fairly homogeneous. On the basis of lithology and chemical analysis this member is considered to be an argillaceous phase of the silicate facies of iron-formation as defined by James (6, p. 263–273). The high content of alumina in analyses A and B relative to the other analyses is probably attributable to the presence of clastic material (cf. average of Precambrian lutites (7), Table 2, p. 57). These two analyses also have significantly lower amounts of iron and carbonate; otherwise the analyses listed are similar to one another and comparable to rocks of the silicate facies elsewhere (6, Table 8, p. 271).

The lower argillite member is as little as nine feet thick at the south end of the range but increases in thickness irregularly northeastward to the vicinity of Canso Bay where in a drill hole it is 40 feet thick. This member is interbedded with the overlying lower sideritic chert member.

Lower Sideritic Chert Member.—This member is continuous throughout the range and was found also in isolated areas along the Temiscamie River. The escarpment along the shore of Lake Albanel consists mainly of this member capped by only a few feet of the more resistant magnetitic member. Inland from this scarp, it has been identified in outcrop only rarely, although it appears in all drill holes that penetrated through the magnetitic member.

In outcrop the rock appears well bedded. The more resistant chert beds

TABLE 2

CHEMICAL ANALYSES OF SOME IRON-FORMATION ROCKS OF THE SILICATE FACIES

	A	B(3)	C(3)	D(3)	E(3)	F(3)
SiO_2	56.64	45.66	38.51	58.49	26.26	37.55
Al_2O_3	10.18	13.93	2.70	0.46	2.20	0.61
Fe_2O_3	4.66	(1)	13.57	15.36	26.93	21.43
FeO	16.07	(1)	21.47	15.04	27.96	24.43
MnO	0.03	0.08	1.81	0.47	1.34	0.71
CaO	0.19	0.23	3.55	1.44	0.54	2.49
MgO	4.09	1.96	3.53	1.32	2.91	2.77
Na_2O	0.04	0.06	0.01	n.d.	n.d.	n.d.
K_2O	1.97	6.03	0.09	n.d.	n.d.	n.d.
TiO_2	0.47	n.d.	0.144	0.040	0.108	0.040
P_2O_5	0.09	n.d.	n.d.	n.d.	n.d.	n.d.
V_2O_3	0.01	n.d.	n.d.	n.d.	n.d.	n.d.
CO_2	0.00	0.35	12.70	7.29	10.40	7.46
S	0.01	0.043	0.005	0.030	0.005	0.005
C	0.00	n.d.	n.d.	n.d.	n.d.	n.d.
C (organic)	n.d.	0.34	0.027	0.018	0.008	0.017
H_2O^-	0.19	n.d. (2)	n.d.	n.d.	n.d.	n.d.
H_2O^+	5.39	n.d.	n.d.	n.d.	n.d.	n.d.
Total	100.03	95.35	98.11	99.96	98.66	97.51
Total Fe	15.62	19.20	26.20	22.43	40.56	34.00

TABLE 2 EXPLANATION

Notes:

(1) Relative proportions of Fe_2O_3 and FeO are uncertain owing to the presence of pyrite and possible organic matter.

(2) H_2O^-, H_2O^+ probably total about five percent.

(3) Analyses of the Temiscamie iron-formation by the Cleveland-Cliffs Iron Co., Ishpeming, Michigan, Owen Hassett, Chief Chemist; organic C and CO_2 by the Mines Experiment Station, University of Minnesota; K_2O and Na_2O by C. O. Ingamells, analyst, Rock Analysis Laboratory, University of Minnesota.

A. Argillite, Sunday Lake mine, Gogebic County, Michigan, three feet (4, p. 102).

B. Lower argillite member (KN 1, 248′), Temiscamie iron-formation, four inches of core. Analysts: see note (3), above.

C. Upper argillite member (R 9, 100–120′), Temiscamie iron-formation, 20 feet of core. Analysts: see note (3), above.

D. Upper argillite member (CW 1, 35–43′), Temiscamie iron-formation, eight feet of core. Analysts: see note (3), above.

E. Upper argillite member, magnetitic zone (R 9, 120–133′), Temiscamie iron-formation, 13 feet of core. Analysts: see note (3), above.

F. Magnetitic iron-silicate member (IG 2, 177–368′), Temiscamie iron-formation, 191 feet of core. Analysts: see note (3), above.

may be up to one foot thick and the less resistant beds, which may be weathered into the face of the outcrop as much as four inches, are mostly less than one inch thick. The color of the exposed surface is typically a light brown to buff.

In drill core the resistant thick beds are white to cream to light brown, depending on the amount of iron carbonate. Where a bed is composed of

more than 50 percent minnesotaite it is light greenish gray. The less resistant beds are brown to dark gray containing a high percentage of iron carbonate commonly with visible stilpnomelane. Graphitic stylolite seams are common between beds. Granules are absent in the area along the lake front, but Neal (8, p. 53) reports granules of stilpnomelane or minnesotaite rimmed by carbonate south of Coom Lake.

An intraformational conglomerate and breccia layer including a two to five inch bed of sideritic quartzite occurs at or near the base of the lower sideritic chert member. This layer has been identified for more than 16 miles along the strike. It is about one foot thick but increases to five feet.

The mineralogic composition of the thick, light-gray beds and the thin, dark-gray beds is quite different. In the light-gray beds the most common mineral is quartz which makes up as much as 60 percent of the bed. The larger quartz grains have a mosaic texture while the smaller grains have irregular to sutured contacts. Throughout most of the range minnesotaite is very common in the chert layers, in some places constituting 70 percent of the bed.

Two carbonates have been identified by x-ray to be siderite and dolomite. Because the N_o of the dolomite is considerably above 1.70 and since it occurs in iron-rich rocks, it is probably the species ankerite. Ankerite as used here is dolomite, with the ferrous content greater than the magnesium content (13, p. 211). Complete mixing cannot exist between siderite and ankerite since only a very limited amount of Fe or Mg can substitute for Ca. Either carbonate may be present to the exclusion of the other or they may occur together. Siderite generally exhibits evidence of replacement by quartz as shown by the configuration of the siderite-quartz contacts. Although the siderite may have early euhedral growth stages outlined by dust-size hematite inclusions, the present outline of the siderite grains or masses is anhedral.

In the light-gray cherty beds ankerite may be present in quantities up to 70 percent of an individual bed. It is generally subhedral with undulant extinction and often has inclusions of quartz, minnesotaite and stilpnomelane. The ankerite is clear but may also be zoned by hematite dust (Fig. 3) showing that part of the ankerite is contemporaneous with hematite as well as the similarly-zoned siderite.

Platy brown stilpnomelane may be concentrated near the border of the light-gray beds; it may also occur in masses resembling granules in outline. The stilpnomelane of these masses is brown near the borders but green near the centers.

Small amounts of anhedral pyrite occur throughout the member. Magnetite is confined to the upper part of the member and is rare.

In contrast to the light-gray beds, the matrix of the thin, dark-gray layers is fine-grained iron carbonate (less than 0.01 mm). Up to 20 percent of a bed may be stilpnomelane, which occurs scattered through the matrix as a mesh of thin fibers up to 0.2 mm long. Dust-size graphite is common in the carbonate matrix of the thin-bedded layers. In beds rich in graphite there is no stilpnomelane, but green chlorite is present. Minnesotaite, magnetite, hematite and pyrite are rare.

Table 3 gives analyses of carbonate-rich rocks of the Temiscamie iron-formation. A few analyses from the Lake Superior region are given here for comparison. Analysis G is from a drill core representative of the lower sideritic chert member of the Temiscamie iron-formation. Unfortunately the validity of this analysis is open to question on account of the low SiO_2 and CO_2 reported. Bearing this in mind, however, all these analyses are quite similar, although a greater prevalence of dolomite in the Temiscamie iron-formation is indicated by the relatively high content of CaO.

North of the mouth of the Temiscamie River the member is between 20 and 40 feet thick. At the south end of the range, however, the thickness is less than 20 feet. The thinning towards the south is consistent with the concomitant thinning of the underlying member and the Boulder Bay quartzite.

Magnetitic Chert Member.—Economically this is the most important member of the Temiscamie iron-formation because of its magnetite content. Owing to its resistant nature it caps the prominent scarp paralleling the lake

TABLE 3

CHEMICAL ANALYSES OF SOME IRON-FORMATION ROCKS OF THE CARBONATE FACIES

	G	H	I	J	K	L
SiO_2	22.71	27.43	36.92	32.2	32.87	42.37
Al_2O_3	0.18	0.23	0.32	1.5	2.46	n.d.
Fe_2O_3	15.57	1.64	1.36	0.6	4.78	1.09
FeO	14.90	30.28	24.56	31.6	30.84	31.41
MnO	0.47	0.77	0.67	1.9	1.33	n.d.
CaO	10.84	6.64	6.87	1.6	0.62	0.50
MgO	3.60	5.04	4.71	2.8	3.58	2.48
Na_2O	0.05	n.d.	n.d.	—	0.00	n.d.
K_2O	0.09	n.d.	n.d.	0.2	0.00	n.d.
TiO_2	n.d.	n.d.	0.008	0.0	0.27	n.d.
P_2O_5	n.d.	n.d.	n.d.	0.8	0.09	n.d.
CO_2	17.11	28.03	24.47	24.8	20.94	21.80
S	0.005	n.d.	0.005	n.d.	0.09	n.d.
C	0.009	0.016	0.019	1.8	0.45	n.d.
H_2O^-	n.d.	n.d.	n.d.	0.2	0.28	n.d.
H_2O^+	n.d.	n.d.	n.d.		1.69	n.d.
Total	85.53	100.08	99.91	100.0	100.29	99.65
Total Fe	22.48	24.66	19.83	25.0	27.25	25.16

G. Lower sideritic chert member (KN 1, 200–220′), Temiscamie iron-formation, 20 feet of core. Analysts: see note (3), Table 2.

H. Upper sideritic chert member (AW 4, 68–78′), Temiscamie iron-formation, 10 feet of core. Analysts: see note (3), Table 2.

I. Non-magnetic lens of the magnetitic chert member (R 9, 183–214′), Temiscamie iron-formation, 31 feet of core. Analysts: see note (3), Table 2.

J. Banded chert-carbonate iron-formation, Iron River district, Michigan, recalculated to total iron content of 25 percent which was considered by James average of the district (6, p. 253).

K. Chert-carbonate iron-formation, Ironwood iron-formation, Gogebic iron range, Iron County, Wisconsin, 12 feet of core (4, p. 91).

L. Carbonate iron-formation, Marquette district, Michigan (6, p. 253, from 16).

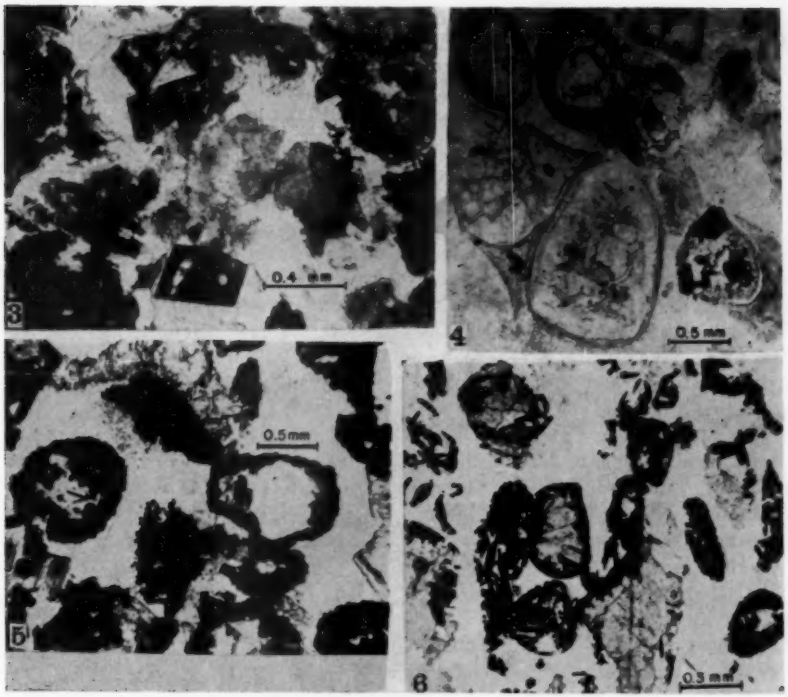

FIG. 3. Lower sideritic chert member. Anhedral ankerite (light to dark gray) showing early euhedral outlines portrayed by hematite dust (dark gray to black). Note quartz (white) replacing iron carbonate. Plane light. (R 9, 272–277′.)

FIG. 4. Magnetitic chert member. Oolites showing syneresis cracks. Note euhedral magnetite. (Al 16, 100′.)

FIG. 5. Magnetitic chert member. Granules bordered by euhedral magnetite. Groundmass is anhedral ankerite (light gray), quartz and rare blades of brown stilpnomelane. Plane light. (SS 23, 60–70′.)

FIG. 6. Magnetitic chert member. Blade-like magnetite protruding into the centers of granules. Groundmass is mainly quartz with some siderite (light gray). Siderite inside some granules. Plane light. (Al 20, 50′.)

front from Kapotagen Bay to Canso Bay. South of the Temiscamie River mouth the top of the magnetitic chert member is close to the level of Lake Albanel; no scarp has formed and outcrops are rare. This member has been traced by drilling in several of the covered areas so that it seems well substantiated that it is continuous from several miles north of Canso Bay southwest to the Richmond River. Several other occurrences have been studied along the Temiscamie River, the most notable in the area south of Coom Lake (8).

In outcrop the rock is pinkish-white with scattered or bedded black to

blue-black hematite and magnetite grains. The rock has a similar aspect in drill core. Gross features such as bedding or other types of segregation cannot be as easily discerned in drill core but oolite and granule textures are more easily recognized.

Quartz is the most common mineral of the matrix in which the magnetite and hematite occur. The recrystallization of the original chert may have been influenced by the presence of granules since the interiors of granules and oolites are generally mosaic quartz in a matrix of fine-grained quartz (Fig. 4).

Magnetite occurs as masses of euhedral grains, as concentrations of euhedral grains in layers, as scattered crystals at the periphery or interior of oolites and as blades (or lentiles) outlining or filling granules (Fig. 5, 6). The magnetite blades are rarely longer than 0.15 mm or wider than 0.03 mm and the octahedra have a diameter less than 0.05 mm. Magnetite rarely makes up more than 50 percent of the rock except in individual beds less than six inches thick.

In areas where hematite is fairly abundant the centers of the magnetite masses and blades may be hematite, but in almost every case hematite also makes up part of the outside edge of the mass or blade. Hematite is ubiquitous but far exceeded in amount by magnetite. Dust-size hematite is scattered throughout the member, and relic textures of oolites, granules and syneresis cracks are excellently delineated by it.

Carbonate occurs throughout the member. Where the texture is banded it may make up almost 100 percent of an individual layer. As in the underlying member the carbonate may be either siderite or ankerite, both commonly occurring in the same thin section.

Stilpnomelane seldom exceeds three percent of the rock. It generally has a platy habit but occurs also as fine-grained granule-shaped masses. Contiguous to magnetite, stilpnomelane contains mainly ferric iron (light to dark brown pleochroism) but with siderite or quartz it contains more ferrous iron (light- to dark-green pleochroism (2), p. 14). In a few thin sections there is evidence that quartz has replaced stilpnomelane, for the edges of the stilpnomelane crystals have been scalloped by quartz.

Minnesotaite occurs as minute radiating needles protruding from a fine-grained confused aggregate of the mineral in quartz. It rarely amounts to as much as five percent of the rock. Green chlorite and pyrite are sparse.

Oolites, granules and syneresis cracks are the most conspicuous texture of the magnetitic chert member. The borders of oolites and granules consist of magnetite with or without associated hematite. The magnetite and hematite generally are in blades (Fig. 6). The magnetite also occurs as octahedra either in the borders of oolites and granules or as minute particles outlining the concentric bands of the oolites. In some cases it appears that the original textures may have been oolitic and that during the process of reconstitution or even during incipient crystallization that in some oolites the concentric bands were obliterated so that only the outside form remains. Figure 7 shows an oolite in which the concentric bands have been only partially destroyed (cf. Figs. 5, 6). Syneresis cracks are common in both

oolites and granules outlined by fine hematite dust in a matrix of carbonate of quartz (Fig. 4).

Magnetite occurs throughout the member without any discernible regular variation in abundance (3). Near the top it is euhedral and blade-like, generally confined to granules or oolites, but with increasing depth the magnetite becomes finer grained (less than 0.05 mm) and occurs in irregular patches or aggregates gradually coalescing into more and more sharply defined layers towards the bottom.

Lenses of abundant hematite occur from place to place along the strike. The hematite occurs as blades or in anhedral masses and only exceeds 0.03 mm in grain size in these hematite-rich lenses. In the area between Kallio Lake and Lake Albanel the upper part of the member may have so little magnetite present that it cannot be detected by a hand magnet.

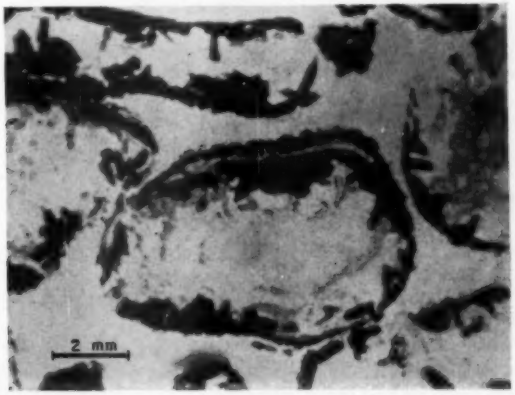

FIG. 7. Magnetitic chert member. Texture shows how the growth of magnetite in an oolite may destroy the concentric banding thereby producing a granule. Plane light. (CE 2, 135′.)

Table 4 lists analyses of hematite- and magnetite-rich iron-formation rocks of the oxide facies. Analyses M and N are representative of the magnetitic chert member of the Temiscamie iron-formation; analysis O is an average of these two. Analysis I, Table 3, is representative of a non-magnetitic lens of the member. Analyses P, Q and R represent rocks of the oxide facies from the Mesabi range, Minnesota and the Gogebic range, Michigan.

In most respects the analyses are similar. However, a major difference does exist between the rocks from the Temiscamie iron-formation and the others in respect to the carbonate content. Both the Ca and the CO_2 content are greater in the Temiscamie iron-formation. The higher Ca and CO_2 content is attributed to the higher proportion of ankerite in the magnetitic chert member compared to similar rocks of the Mesabi range.

The average thickness of the magnetitic chert member is about 140 feet computed from over 30 drill holes along a strike length of 35 miles parallel

to Lake Albanel. Between Kallio Lake and Plateau Lake the average thickness is 132 feet and in the area south of Coom Lake the thickness is probably close to 200 feet. The contact with the underlying member is gradational and is marked by a gradual increase of magnetite.

Upper Argillite Member.—This member was named in the field before microscopic examination and chemical analysis had shown that the rock was actually of the silicate facies, not an argillite.

TABLE 4

CHEMICAL ANALYSES OF SOME IRON-FORMATION ROCKS OF THE OXIDE FACIES

	M	N	O	P	Q	R
SiO_2	39.50	22.70	31.10	48.75	48.28	34.44
Al_2O_3	0.44	0.31	0.37	0.17	0.23	0.85
Fe_2O_3	29.21	22.07	25.64	30.31	22.47	30.54
FeO	18.51	23.20	21.35	13.62	17.79	22.06
MnO	0.12	1.06	0.59			0.21
CaO	2.71	4.49	3.60	0.89	1.46	1.72
MgO	2.00	3.88	2.94	1.48	2.94	2.30
Na_2O	n.d.	n.d.	n.d.	n.d.	n.d.	0.00
K_2O	n.d.	n.d.	n.d.	n.d.	n.d.	0.13
TiO_2	0.040	0.014	0.027			0.02
P_2O_5	n.d.	n.d.	n.d.	0.07	0.07	0.07
CO_2	6.22	21.18	14.10	2.77	5.05	7.36
S	0.129	0.005	0.067			0.01
C (organic)	0.017	0.016	0.016	0.04	0.08	0.04
H_2O^-	n.d.	n.d.	n.d.			0.17
H_2O^+	n.d.	n.d.	n.d.	1.55(1)	1.36(1)	0.44
Total	99.90	98.92	99.80	101.18	99.73	100.36
Total Fe	35.61	33.83	34.72	31.08	28.61	39.47

Note: (1) Dried at 100° C.

M. Magnetitic chert member (R 9, 214–272′), Temiscamie iron-formation, 58 feet of core. Analysts: see note (3), Table 2.

N. Magnetitic chert member (R 9, 133–183′), Temiscamie iron-formation, 50 feet of core. Analysts: see note (3), Table 2.

O. Average of M and N.

P. Lower cherty division, Mesabi range, Minnesota, weighted average calculated by James (6, p. 263) from five analyses representing 110 feet of drill core (2, Table 7, p. 58).

Q. Lower cherty division, Mesabi range, Minnesota, weighted average calculated by James (6, p. 263) from six analyses representing 110 feet of core (2, Table 8, p. 59).

R. Jasper-magnetite iron-formation, Ironwood iron-formation, Gogebic iron range, Gogebic County, Michigan, representing 11 feet of core (4, p. 100).

Because of the lack of resistance to weathering of this member it seldom crops out. It is best exposed at the foot of a small bay east of the northern Snowshoe Island, although it is found in drill holes throughout the length of the range.

In outcrop the argillite is dark green to greenish-black in color, well jointed and massive. The lower 10 to 20 feet may be magnetic. The upper part of the member becomes thinly bedded with excellent bedding parting. Oolites, granules and other textures are absent.

The most abundant minerals are siderite and ankerite. They are mostly anhedral and fine grained forming the matrix for the other minerals. Stilpnomelane occurs as a mat of lath-shaped crystals in certain layers of carbonate (Fig. 8). In places the plates of stilpnomelane are large enough so that they can be seen in hand specimen and comprise as much as 90 percent of

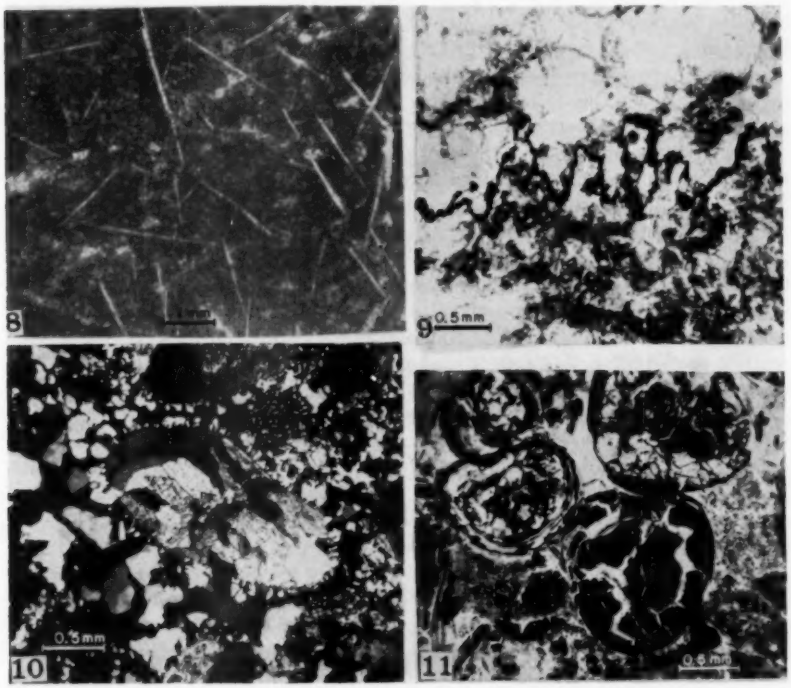

FIG. 8. Upper argillite member. Lath-shaped crystals of stilpnomelane (light gray) in a groundmass of fine-grained carbonate. Plane light. (SW 3, 128′.)

FIG. 9. Upper sideritic chert member. Graphitic stylolite seam. Note the faint granule outlines in the groundmass of siderite. Plane light. (SW 3, 78′)

FIG. 10. Upper sideritic chert member. Carbonate granule bordered by fine-grained quartz. With analyzer. (AI 20, 38′)

FIG. 11. Upper sideritic chert member. Oolites (?) with syneresis cracks. Quartz groundmass. Plane light. (PE 4, 61′.)

a layer. The abundant stilpnomelane accounts for the greenish hue of the rock.

Angular grains (less than 0.05 mm) of quartz occur sporadically throughout the member and may be concentrated in thin layers. They might be of colloidal origin, but because of their angularity, the lack of evidence of remnants of true chert and the presence of chloritic matrix, they are considered more likely to be detrital. Graphite occurs only along stylolite seams.

Magnetite is found only in the lower 20 feet of the member. It is euhedral; 90 percent of the crystals are between 0.02 mm and 0.003 mm in size. It is scattered evenly through the fine-grained carbonate matrix but may be concentrated in thin layers.

Analyses C, D and E (Table 2) represent rocks from the upper argillite member. Compared to analysis B of the lower argillite to which the upper argillite bears a close megascopic resemblance, the analyses as well as the mineralogies show significant differences. As mentioned above, there is less alumina but more iron and carbonate in the rocks of the upper argillite member than in the lower argillite. This might be expected by the rare presence of detrital material and the increase in abundance of siderite and ankerite in the upper argillite rocks. Although the alumina is still more common in these rocks than in iron-formations as a whole, it is probably contained in the iron silicates rather than in detrital minerals. For instance, stilpnomelane may contain up to about 7 percent Al_2O_3 (2, p. 10) and minnesotaite up to about 1.5 percent (1). The rock of analysis E contains up to 40 percent magnetite, which is reflected in the high total iron content. On the basis of lithology and chemical analysis, the upper argillite member is considered to be an example of the silicate facies of iron-formation.

The thickness of this member ranges from four to 46 feet. The greatest thickness was encountered east of the Snowshoe Islands.

The contact with the underlying magnetitic chert member is generally sharp but minor interbedding may occur. The amount of magnetite in the upper argillite member gradually decreases upward from the lower contact. The contact with the upper sideritic chert member is an extensive zone of interbedding.

Magnetitic Iron-silicate member.—This member has been recognized only in some of the fault blocks of the iron-formation along the Temiscamie River. Outcrops are few and only a limited amount of diamond drilling has been done in these areas.

In outcrop the rock consists of alternating black and white, thin (less than 2 cm) layers. The black layers consist of magnetite and stand out in relief. Each layer may vary in thickness along strike, which gives this member an appearance similar to the "wavy banded taconite" of the Mesabi range, Minnesota. A few layers of pink chert, layers of pink chert fragments, and intraformational conglomerates may be followed for many feet. Thin, well-developed bedding is the most diagnostic feature of this member.

Magnetite is euhedral but much more fine grained (less than 0.03 mm) than that in the magnetitic chert member discussed above. It may be scattered but is generally concentrated in thin layers. These layers may be so closely spaced that in hand specimen they appear as one solid layer.

Plates of stilpnomelane make up most of the matrix of the magnetitic layers and occur also with minnesotaite and carbonate in the dark-green layers and to a lesser extent in the light-colored chert beds. Minnesotaite may make up as much as 95 percent of a light-colored layer. In general, quartz is confined to thick layers containing minnesotaite and iron carbonate. Quartz-rich beds may contain much fine hematite which colors the rock pink to red.

Both ankerite and siderite are present, the ankerite generally occurring in a matrix of quartz.

Analysis F, Table 2 represents 191 feet of core from the magnetitic iron-silicate member. It is strikingly similar to the three accompanying analyses (C, D and E) of the upper argillite member.

The thickness of this member is difficult to determine because of much repetition by faulting; a rough estimate is 100 feet.

Where the underlying and overlying units are preserved their lithology is similar to the upper argillite member and the contacts with the magnetitic iron-silicate member are gradational. However, because the member occurs only in fault blocks isolated from rocks of known stratigraphic position and because within these fault blocks considerable repetition of beds by faulting has taken place, the exact position of the member in the stratigraphic column is in doubt. On the basis of the structural and petrologic evidence now available the magnetitic iron-silicate member is considered to be either a lens in the upper argillite member or a simply a facies of that member. Because of the geographical extent and potential economic importance of the rock type it has been considered as a separate member of the Temiscamie iron-formation.

Upper Sideritic Chert Member.—Outcrops of this member have been seen as far north as Canso Bay and extend southward to the vicinity of the Richmond River. The main outcrop area is in the western part of the plateau between the scarp on the east shore of Lake Albanel and the Temiscamie River.

In outcrop the upper sideritic chert member appears blocky, with excellent bedding. This effect is caused by the relatively rapid decomposition of the thin carbonate-rich beds. Because of the weathering of the siderite in the rock the member has a light brown to buff color. In drill core light-gray bands, predominantly of quartz and up to several feet thick alternate with thin light-brown bands up to several inches thick. In a few places the light-gray bands are specked with gray to brown spots of iron-rich carbonate up to one-half inch in diameter. Oolites and granules commonly occur in these spots and in the surrounding chert bands.

The essential minerals of the upper sideritic chert member are quartz, siderite, ankerite and stilpnomelane. Chlorite, minnesotaite, pyrite, graphite, magnetite and hematite together make up less than two percent of the member.

Quartz in some beds may comprise up to 90 percent and in other beds only a few percent. Most of the carbonate is clouded by dust-size inclusions that indicate early crystal outlines. The larger grains that have few to no inclusions may have crystallized later. Stilpnomelane occurs irregularly throughout the member as radiating fibers, or plates of sheaves. It makes up less than five percent of the rock. In contrast to the lower sideritic chert member minnesotaite makes up less than one percent of the chert layers. Graphite is extremely fine grained and found either in very thin discontinuous lenses (0.005 mm $\times$ 0.5 mm) or along stylolite seams (Fig. 9). Magnetite, hematite, pyrite and pyrrhotite have been observed as small anhedral grains.

Granules, oolites, syneresis cracks, spherulites and pisolites are all ob-

served within this member. Granules are present in almost every specimen of the upper sideritic chert member. Typically they are seen as outlines of fine brown to black dust in siderite or ankerite masses and bands. Where the granules are made up of carbonates in a matrix of quartz, a layer of fine-grain quartz surrounds the granule (Fig. 10). Oolites are seldom well preserved or well formed; spherulites, pisolites and other textures are rare.

Analysis H, Table 3, is representative of the upper sideritic chert member. The chemical composition of similar rocks has been discussed above.

The upper sideritic chert member is considered to be one of the thicker members of the Temiscamie iron-formation. No drill hole goes through its entire thickness, but from structural evidence in the vicinity of Ruth Lake it is believed to be at least 100 feet thick.

The base of the overlying Kallio formation is marked by an increase in fine-grain quartz and a decrease in siderite compared to the upper sideritic chert member of the Temiscamie iron-formation. In the one outcrop where the contact with the overlying Kallio formation was observed, the base of the Kallio formation was identified by a sequence of finely bedded black chert without any siderite. The contact with the sideritic chert below seemed to be quite abrupt.

Kallio Formation

The Kallio formation lies in the eastern half of the area between Lake Albanel and the Temiscamie River. It is highly folded, faulted and sheared; in most outcrops both the slaty cleavage and the bedding are vertical. Neilson (9, p. 68) estimated the thickness to be about 800 feet.

Feldspathic graywacke, subarkose and slate are the more common rock types. In thin section angular grains of quartz may make up as much as 80 percent of the rock or may be entirely absent. They are less than 0.2 mm in diameter and occur in a matrix of fine-grained quartz and mica along with graphite. Somewhat smaller plagioclase grains also occur, but as less than five percent of the rock.

Graphite, either with or without fine-grained pyrite, is ubiquitous. In the slaty rocks graphite may make a standard thin section entirely opaque. Pyrite is common in all parts of the formation. Of all the rocks in the area the Kallio formation most closely approaches the sulfide facies of iron-formation as defined by James (6, p. 248–251).

The relationship of the Kallio formation to the underlying Temiscamie iron-formation has been discussed above. The Kallio formation has been brought into juxtaposition with various members of the iron-formation along the Temiscamie River by faulting. No rocks have been found stratigraphically above the Kallio formation; thus it is believed to be the youngest remaining consolidated formation in the area.

STRUCTURE

Along the Albanel lake front the Temiscamie iron-formation dips gently (less than 15°) to the southeast. Recently, detailed mapping and more

closely spaced drilling have shown many minor rolls and flexures. The change from the regional dip of five degrees is generally on the order of two to five degrees, with rare instances of actual reversal of dip in small areas.

These gentle dips are terminated on the southeast by a series of sub-parallel faults in the Kallio Lake-Ruth Lake-Plateau Lake area. The largest of these faults has a vertical displacement of about 500 feet and a strike length of over eight miles. This fault trend may continue southwest of Kallio Lake as well. Southeastward, rocks of the Kallio formation are sheared and exhibit excellent slaty cleavage. Between the sheared Kallio slate and the main Mistassini fault zone along the Temiscamie River, rocks of the Mistassini group including the Temiscamie iron-formation are block faulted and in places overturned. The general strike of the faults, the rock cleavage and the fold axes trends northeast paralleling the Mistassini fault zone and the intensity of their deformation increases southeastward towards the Mistassini fault zone. These structures are considered to be part of, or at least attributable to, movements along this fault zone between rocks of the Mistassini group and those of the Grenville metamorphic complex. A few minor faults striking a northwesterly direction have been found, but in general their displacement is small and their strike length is short.

PARAGENESIS

Silicate Facies Rocks.—Included here are the lower argillite member, the upper argillite member and the magnetitic iron-silicate member. The environment in which the lower argillite member was deposited was probably intermediate between that which might produce an argillite and that which might produce rocks more typical of the silicate facies of iron-formation. One main characteristic was the highly reducing nature of the environment. Sedimentation was slow, particles of silt size or smaller being deposited almost exclusively. The presence of detrital quartz and plagioclase suggests that the body of water was not entirely stagnant. The occurrence of cross-bedding and lenses of detrital particles further indicates that currents were active from time to time. The layered silicates that make up most of the rock are probably derived from the original silty and clayey sediments that have been since only partially recrystallized.

The upper argillite member is a typical nongranular laminated silicate facies rock (6, p. 268–270). The main minerals are stilpnomelane, minnesotaite, iron carbonate and quartz. The iron silicates are probably a diagenetic reconstitution from iron-rich material of silt size or smaller although some may have crystallized directly from solution. The magnetitic iron-silicate member differs from the upper argillite in that it contains appreciable quantities of magnetite. This magnetite is associated with the iron silicates or quartz, but seldom with ankerite or siderite. From the textural evidence available it seems probable that the iron silicates and magnetite, where present, crystallized early and continued to form during the subsequent crystallization of iron carbonate and chert. The relative amount of these minerals from layer to layer is probably due to the composition of the chemical

and clastic material prior to crystallization and reconstitution as well as to the local Eh and pH.

Carbonate and Oxide Facies Rocks.—Grouped here are the lower and upper sideritic chert members and the magnetitic chert member. They are discussed together because of their similar paragenesis and because they are devoid of any recognizable detrital material.

There is no evidence that any of the constituents were introduced later or moved any great distance after their chemical deposition so that each layer, or at the most two adjacent layers, may be treated as a closed system. The following are the conditions and circumstances under which such rocks might have been formed. At the bottom of the shallow basin of deposition silica gel was coagulated. Trapped in this gel were various ions; the most important were O^{--}, CO_3^{--}, Fe^{++}, Fe^{+++}, Ca^{++}, Mg^{++} and Mn^{++}. In the zone between the gel and the water, granules and oolites were being formed, perhaps aided by oscillations of the water.

Siderite and dust-size particles of hematite formed among the first of the minerals. This is indicated by the euhedral blade-like siderite outlined or zoned by hematite dust. The siderite continued to grow after the hematite ceased to be deposited, their final anhedral shape being an expression of the limited space left by other contemporaneously crystallizing grains. Much of this siderite is not considered to have undergone subsequent recrystallization because the early hematite-dust stage is continuous with the later dust-free part of an individual siderite grain and the present crystal boundaries do not cross the early stage crystal faces marked by the hematite dust. As more and more siderite crystallized the iron content of the remaining portion of the layer was much diminished. Correspondingly the calcium, magnesium and manganese increased. As almost no calcium can be fitted into the structure of siderite the remaining carbonate crystallized in a dolomitic double salt structure, such as ankerite, the exact composition of which depended upon the cations available.

As shown by the syneresis cracks outlined by hematite dust (Fig. 4, 11), the silica gel gradually became desiccated crystallizing into chert. The silica was also being used to form stilpnomelane and minnesotaite. Chert probably crystallized simultaneously with some of the siderite. There are textural indications (Fig. 3), however, that later some quartz may have replaced siderite as the siderite was reconstituted to form ankerite with the excess calcium and magnesium. The final stages of ankerite and chert crystallization probably coincided because ankerite has poikilitic inclusions of chert near the outside edges of the ankerite grains.

The abundance of hematite and magnetite in the magnetitic chert member indicates a high ratio of Fe^{+++} to Fe^{++} in the original precipitate as well as a different Eh and pH from that attending the formation of the sideritic chert members (4, p. 134). The blade-like habit of some of the magnetite and hematite indicates that much of it may have been pseudomorphic after flat rhombohedral crystals of siderite that had started to grow into or out from the borders of oolites or granules (Fig. 6). Where magnetite occurs as very small octahedra either concentrated at the borders of oolites and gran-

ules or scattered, it may have been one of the first minerals to crystallize. Later magnetite, resulting from reconstitution of siderite due to changing Eh or pH conditions and the concentrations of ferric iron, then crystallized in the blade-like habit along with ankerite and chert until final lithification.

Thus in the closed system of one layer the minerals formed in an orderly sequence depending upon the original chemical constitution of that particular layer. An adjacent layer, having a different original composition, would have a different mineral composition.

CONCLUSIONS

1. The Temiscamie iron-formation has been divided into six members. The environments of deposition of these members are considered to be similar to those of other Precambrian iron-formations of comparable lithology.

2. All the members of the Temiscamie iron-formation can be classified as particular facies of iron-formations proposed by James.

3. The structure of the Lake Albanel iron range on the west is simple with the rocks dipping gently to the southeast. Near the Temiscamie River rocks of the Mistassini group are folded and block faulted along the Mistassini fault zone, which is a segment of the Grenville fault. However, rocks of the iron-formation show evidence of only low-grade metamorphism.

4. The composition and presence or absence of minerals within individual layers were dependent upon the original composition of each layer. There was little migration of ions from layer to layer.

5. The paragenesis of the minerals in the iron-formation is simple. Siderite, chert and dust-size hematite were the first minerals to form. Stilpnomelane and minnesotaite also began crystallizing early. Magnetite in the form of octahedra was contemporaneous with siderite and chert. With progressive crystallization, less and less iron remained in the uncrystallized portion of the layer. The remaining Fe, Ca, Mg and Mn crystallized into a dolomitic structure, such as ankerite, depending upon the cations immediately available. The magnetite and hematite that have a blade-like habit are considered to be pseudomorphic after the early flat rhombohedral crystals of siderite.

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WALL-ROCK ALTERATION AT THE CEDAR BAY MINE CHIBOUGAMAU DISTRICT, QUEBEC

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ABSTRACT

The Cedar Bay Mine, Northern Quebec, is entirely within the Chibougamau gabbro-anorthosite complex. The copper and gold minerals occur as replacement bodies and possibly cavity-filling along faults and shears. Because the host rock is essentially of one composition, an exceptional opportunity for the study of alteration is available. The differences in modes of occurrence and quantities of alteration minerals make it possible to delimit alteration zones, which are parallel the ore shoots. The thickness of the alteration zones varies directly with the thickness of the ore shoots. The use of these zones is valuable in estimating the proximity to ore.

INTRODUCTION

THE Chibougamau mining district is in Northern Quebec about 300 miles north of Montreal. It may be reached by railroad or airplane from Senneterre, or by railroad or gravel road from the Lake St. John district. It has long been known to contain deposits of economic minerals and, in the last two decades, has received much attention from prospectors and others interested in discovering mineral deposits. The Cedar Bay deposit on Doré Lake was one of the first discovered and has been examined many times. Up to now, however, no complete and systematic study has been made. This paper is part of a thesis (4) based on a study of the Cedar Bay Mine and the surrounding area.

GEOLOGY

The Chibougamau mining district is near the southeast boundary of the Temiscamian subprovince as classified by Wilson (6). The Temiscamian subprovince of Quebec has meta-sedimentary, meta-volcanic and intrusive rocks. The intrusive rocks are significant in this study and may be divided into four types (1): a) Intrusives genetically related to Archean-type volcanic activity, b) Early Precambrian dioritic, gabbroic and ultra-basic intrusives, c) Early Precambrian granitic intrusives and, d) Late Precambrian basic dikes.

Type "b" includes the Chibougamau complex, a large stratiform mass of layered anorthositic and gabbroic rocks which is the host for most of the deposits in the Chibougamau district. Mawdsley and Norman (2) have mapped the Chibougamau area. They and others have shown that the complex rocks probably were originally horizontal and were folded with the enclosing Keewatin rocks and probably the Timiskaming rocks. The calcic feldspars of the anorthosite were altered to albite or oligoclase, and some of

the relatively iron-poor epidote minerals were formed. This gave rise to the general country rock at Cedar Bay, which is called meta-anorthosite. Rocks of the complex underlie a large part of Doré Lake, as is shown on Figure 1. The complex there is composed mostly of gabbro and anorthosite and their metamorphic derivatives.

The anorthosite, where fresh, is white to gray in color and contains labradorite or bytownite. However, the fresh rock makes up only a minute portion of the whole mass and the major part is meta-anorthosite. Meta-anorthosite is the only variety found at Cedar Bay. This rock is conspicuous

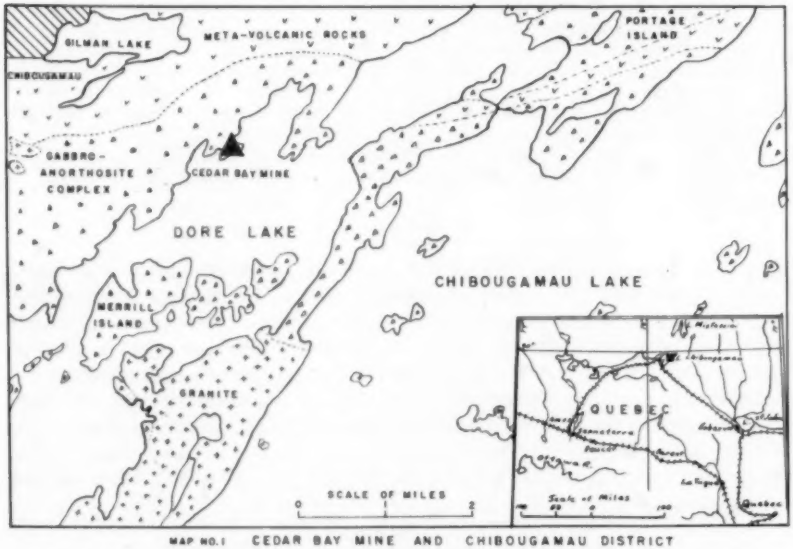

FIG. 1. Cedar Bay mine and Chibougamau District. Map shows general geology and location.

for its crushed appearance, and its uniform composition and appearance over long distances. Hydrothermal alteration changes these aspects.

Other rocks found at Cedar Bay are diorite porphyry and quartz diorite porphyry dikes and their metamorphosed and metasomatized equivalents, the gray and black dikes.

Structurally, the Cedar Bay area is complex. Several types of structural features are recognized, as follows: a) strike faults (E–W), b) cross faults (NE), c) shears (NW), and d) transverse faults (N. 25°–45° E.). The ore shoots and the associated dikes have been controlled by these structural features. The strike faults and shears are pre-ore and contain most of the ore deposits, whereas, the cross faults and transverse faults are mostly post-ore and have been seen to cut the ore, and are not known to contain ore

shoots. They do not contain the porphyry dikes nor the ore-indicator type of alteration such as is found in the strike faults and shears.

Because the structural features have exerted such strong influence on the ore, and because the host rock originally was nearly of uniform composition, the Cedar Bay mine area offers an exceptionally good place for the study of wall rock alteration.

ALTERATION

The Chibougamau complex rocks in the vicinity of Cedar Bay have been altered to form three main rock types: a) tombstone meta-anorthosite formed from the alteration of coarsely crystalline anorthosite, b) sericite meta-anorthosite and, c) chlorite meta-anorthosite.

While examining 250 thin sections it was noted that certain alteration minerals seem to be concentrated near the veins. After the study was completed, the thin sections were reviewed, and a zone number was assigned to each section on the basis of the alteration minerals present. The criteria used to make the assignments are shown in Table 1. These significant zone numbers were then plotted on a plan and it was found that they are parallel to and surround the ore zones. The alteration zones make much larger "targets" for drilling or surface exploration than the veins themselves.

It may be seen from Table 1 that the changes in alteration minerals from zone to zone are qualitative as well as quantative and may be subtle. A more detailed explanation of some of the mineral changes may be helpful in understanding the classification.

Chlorite.—The chlorites are the most widespread of the alteration minerals at Cedar Bay. They occur in every rock type, indeed in almost every slide. They are of various compositions as determined by their different optical properties. They may be classified into two principal types designated I and II.

Characteristics	Chlorite I	Chlorite II
optic sign	positive	negative
elongation	negative (length fast)	positive (length slow)
chemical character	high Mg	high Fe
interference colors	brown to tan	blue to light blue

Most other optical properties are of little use in classifying the chlorites, but those given are usually sufficient. Price (5) has made a study of the chlorites while investigating alteration at Noranda. The above classification is somewhat similar to that used by him, although the applications differ.

From Table 1, it may be noted that the most common type of chlorite found is chlorite I, whereas, that found in and near the ore zones is chlorite II. Quite independently of rock type, as an ore zone is approached at Cedar Bay, the chlorites change from poorly-formed crystals to well-formed crystals, and the chlorite I crystals become chlorite II crystals. Rosettes as illustrated in Figure 2 are typical of the chlorite II found near ore zones.

Because of its ubiquity and almost unfailing adherence to the rule, chlorite is probably the best ore indicator at Cedar Bay.

Epidote Group.—Zoisite, clinozoisite and pistacite (common epidote) have been identified. Zoisite is mostly of the iron-rich, β-zoisite type. A few examples of the α-zoisite (iron-free) type occur but they are not significant quantatively. Where zoisite is not abundant, it occurs as isolated crystals in the centers of plagioclase grains. As it becomes more abundant, the crystals join to make aggregates that may make up most of a thin section.

Zoisite is commonly restricted to former feldspar grains, and it may constitute as much as 75 per cent of the slide, but in most thin sections it amounts to 5 to 30 per cent. It commonly occurs with epidote to which it

TABLE I. CLASSIFICATION OF ALTERATION MINERALS

Zone	CHLORITE	EPIDOTE	APATITE	CARBONATE	ZOISITE	SERICITE	FELDSPAR	ORE MINERALS	ACTINOLITE
	Chlorite II Large crystals Rosettes, semi-rosettes	If present Well-shaped crystals	Large to medium prismatic crystals	If present usually euhedral to subhedral crystals	If present is Fe-rich variety or altered to epidote	Usually present as good crystals (muscovite) relatively large	Little or none	Present in substantial quantities	Fresh acicular crystals or may be completely altered to quartz and chlorite
1 ore	Elongated crystals abundant-medium to good pleochroism rarely isotropic commonly occurring in veinlet	clear usually in veins or as veinlets	corroded and healed by quartz, carbonate, etc.						
2 near ore	Same as Zone 1 except ore minerals sparingly present or absent.								
3 Transitions	Chlorite II possibly some Chlorite I rare as veinlets Semi-rosettes to poor crystals poor to medium pleochroism rare to abundant maybe isotropic	poor to good crystals present in veinlets or disseminated may be clear may surround zoisite	medium to small crystals Hexagonal sections common	may be present as subhedral crystals and as veinlets	May be present probably as Fe-rich variety	Present as medium to good crystals, medium sized crystals except in dyke where may be small to large	Sodic feldspar be present usually highly altered	Probably absent	Probably absent
4 no ore	Chlorite I possibly little Chlorite II - medium to good crystals--including rosettes-poor to medium pleochroism-nearly isotropic, few chlorite veinlets	poor crystals dirty appearing crystals may be small to large	very small crystals or none	present as crystals, but mostly as non-descript blebs	May be present but probably variety low in Fe.	If present, mostly as very fine crystals	Sodic feldspar may be present altered	Absent	Probably absent
5 no ore	Chlorite I (no type II) poor crystals most common, nearly isotropic, few or no chlorite veinlets	rarely present dirty and definitely alteration of adjacent feldspar probably as medium to small grains.	very small crystals or none	same as Zone 4	Same as Zone 4	Same as Zone 4	Sodic feldspar present as good, well formed crystals, usually clear	Absent	Probably absent

alters. In a few slides an albite grain is surrounded by a zoisite rim, which in turn is surrounded by an epidote rim. This probably was caused by alteration of the albite to zoisite with later hydrothermal alteration to epidote by iron-rich solutions. Zoisite also surrounds clinozoisite, the zoisite being the iron-rich variety. Zoisite is common except near the ore zones where it is generally replaced by epidote. Thus its value as an ore indicator is mainly negative.

Epidote is the next most common mineral of this group found at Cedar Bay. It is most common as a replacement of zoisite and clinozoisite in the position of the former feldspar grains where feldspar may or may not still

exist. It is seen to occur with albite, sericite and zoisite or clinozoisite and is most widespread as a cloudy mineral in small to medium sized grains in the interstitial position of the meta-anorthosite. It is also present as small veinlets cutting the meta-anorthosite. The veinlets commonly contain better

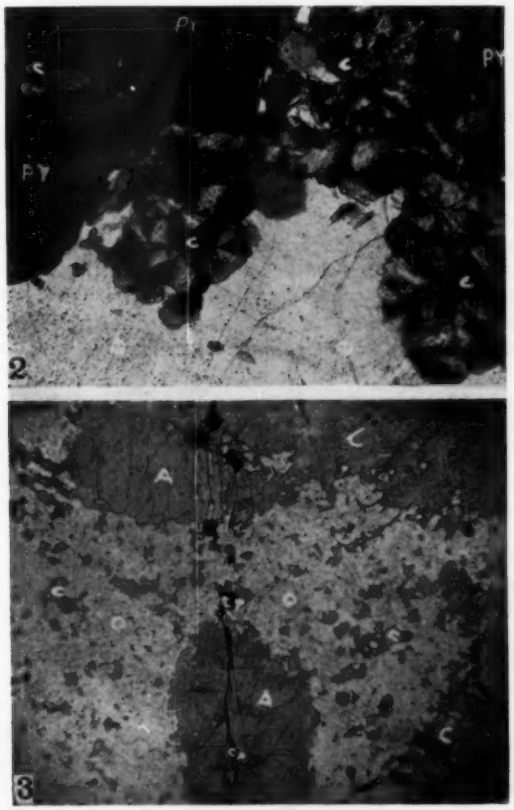

FIG. 2. Photomicrograph of chlorite rosettes in vein with quartz (Q) and pyrite (P). This texture is found only near ore minerals at Cedar Bay. Nicols crossed; × 65.

FIG. 3. Photomicrograph of anomalous apatite (A), chlorite (C), and quartz (Q). Note apatite is cut by chalcopyrite veinlet (black). Nicols uncrossed; × 20.

and clearer crystals than does the matrix. From its mode of occurrence epidote seems to be a late-formed mineral, possibly associated with the ore solutions. Its presence as well-shaped, clear crystals in veinlets indicates a proximity to ore zones at Cedar Bay.

Clinozoisite is not widespread. Its mode of occurrence is similar to that of zoisite. It is replaced by β-zoisite and epidote, whereas it replaces only feldspar. It is a negative indicator of the proximity of ore zones at Cedar Bay.

Apatite.—The apatite at Cedar Bay is of at least two types and origins. That occurring in the dikes is sub-megascopic and has the optical properties generally associated with the mineral; e.g. moderate refringence, uniaxial negative character, hexagonal outline. Another type found near the ore zones has anomalous optical properties. In all thin sections examined it is biaxial positive. McConnell and Gruner (3) have described biaxial apatite from Arkansas that contains minor amounts of carbonate. They mention biaxial negative apatite, but not the biaxial positive variety. Chemical and X-ray analyses definitely established the Cedar Bay mineral as apatite. It was noted that the mineral effervesced in hydrochloric acid. Possibly CO_2 in the lattice caused the anomalous character.

The anomalous apatite (Fig. 3) has been found at various places throughout the mine, but always very close to the ore. Thus it is a good ore indicator. Unfortunately, the fact that it is present only in the immediate vicinity of the ore zones decreases its value. It is possible, however, that this mineral may be present in zones which, along strike, are potential ore zones and thus it may be a useful ore indicator. The anomalous apatite is distinguishable in hand specimen from the normal apatite. It is commonly in grains up to 1 cm, which are pink or white. They are especially distinctive because they occur in a dark green or black matrix.

Actinolite.—Fresh amphibole was seen in only a few specimens. It has the following properties:

$2V = 75° \pm$, negative optical character
$Z \wedge c = 27° \pm$, optic axial plane parallel to (010)
Birefringence 0.020–0.025
$\gamma = 1.665 \pm .005$ Z = pale blue green
$\beta = 1.657 \pm .005$ Y = olive green
$\alpha = 1.664 \pm .005$ X = pale yellow green
absorption, $Z > Y > X$
specific gravity 3.08

A search of the commonly used tables of optical properties of minerals showed no amphibole exactly like this, but it resembles an actinolite more than the other amphiboles. It commonly has a plumose habit and is altered to chlorite. Chlorite with a plumose or sheaf-like habit is common near the ore zones. Thus it is thought that the actinolite was once more common at Cedar Bay than it is now.

The writer found several localities where a vein with sulfides is separated from the wall rock on one or both sides by an actinolite vein or altered actinolite vein. These veins show the acicular texture, but along strike were found to change to a rock of the same composition whose acicular texture is visible only on thin section. The invariable association of ore minerals and actinolite make it a valuable guide to ore at Cedar Bay.

Carbonate.—Carbonate occurs in all the rocks at Cedar Bay, and its presence can be explained reasonably. In the degradation of the bytownite of the anorthosite to albite and oligoclase of the meta-anorthosite, large amounts of calcium were released. This calcium combined with carbon dioxide of hydrothermal origin to form the calcium carbonate. This hypothesis, if true, would explain the greater part of the carbonate found in the rocks, as it is calcite. Some of the carbonate is dolomite, whose magnesium probably came from the degradation of the ferromagnesian minerals, pyroxene and amphibole. The iron of the siderite, which is also present, may have come from the same source, although the concentration of the siderite in the veins suggests that part of the iron is of hydrothermal origin.

The carbonate, with the exception of siderite, is too widespread to be a really good ore indicator. However, the concentration of carbonate in shear zones helps in working out the structure of the area as well as to indicate the degree of alteration and thus may be of value in the search for ore. The habit of the carbonate in the various alteration zones is shown in Table 1.

Quartz.—Quartz is present in all the rock types at Cedar Bay. Some of the quartz probably developed during regional alteration of the anorthosite, but most is an alteration product for it is much more abundant in the altered than in fresh rocks. Fresh anorthosite contains little or no quartz, whereas the meta-anorthosite contains from sparse to abundant quartz grains, especially near the ore zones. A similar statement can be applied to the dikes.

Several specimens of the gray dike were chosen for X-ray diffraction analysis. Because of the variation in amounts of minerals other than quartz, the quartz percentages did not give a true idea of the variations between specimens. The tenors of quartz, chlorite and mica were recalculated to 100 per cent, omitting calcite, and were plotted on a ternary diagram, Figure 4. It was possible to locate the specimens on a surface geological map, and estimate the distance of the specimen from the nearest ore mineralization.

A study of the ternary diagram shows that those specimens richest in quartz are closest to ore. Thus quartz is fair ore indicator at Cedar Bay, but is probably better used with some of the other minerals as shown in Table 1.

Micas.—Mica is found in practically all the altered rocks at Cedar Bay, especially the sheared rocks. The quantity of mica seems to be dependent on the intensity of shearing that has taken place, and its presence is also a measure of the effectiveness of hydrothermal alteration. Some slides contain grains of mica large enough to be identified as muscovite; the same material in finer grains is called sericite in harmony with the accepted definition (7). It is noteworthy that the criteria for distinguishing between sericite, illite, and the other fine, scaly alteration products are not entirely satisfactory.

In some fresher specimens of meta-anorthosite, sericite occurs as minute flakes, which clouds the feldspar. The mica has preferred orientation in which the greater dimensions of the flakes are parallel to the (010) cleavage and, therefore, parallel to the albite twins of the albite. Other preferred orientations are parallel to the basal cleavage and the pericline twin planes. Where both are seen, a mesh structure is formed.

Sericite is particularly abundant close to the ore, but is almost never the gangue for the ore minerals. Rather, it is commonly separated from them by quartz, and/or chlorite, and/or carbonates. Near ore the sericite seems to form larger crystals than away from ore and tends to be in rosettes that resemble those of the chlorite. However, in a few places crystals of muscovite accompany ore. The shear zones contain abundant sericite and in places are almost entirely made up of this mineral (or minerals). Sericite is valuable as an ore indicator mostly in a qualitative sense as shown on Table 1.

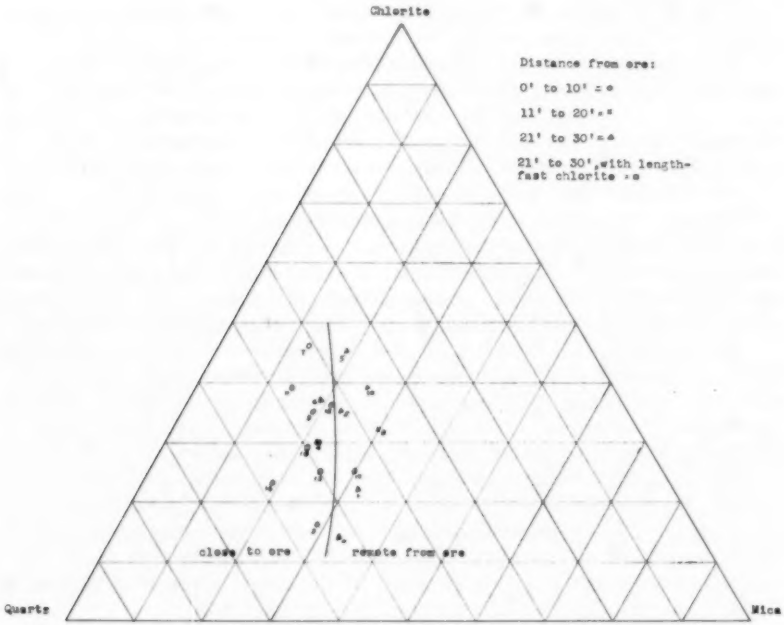

FIG. 4. Plotted results of X-ray analysis of gray dike. Note the increase in relative quantities of quartz near ore.

Feldspar.—The most calcic feldspar found at Cedar Bay is oligoclase; elsewhere in the Chibougamau complex, feldspars as calcic as bytownite occur. The feldspars near Cedar Bay were more calcic than they are now, as indicated by a study of fresh and altered anorthosite specimens and their alteration products, especially epidote group minerals.

Fresh sodic feldspar is seldom seen near ore zones. Probably this is true for several reasons, among which is the fact that intense alteration (commonly with potash metasomatism) accompanies the ore zones. The shearing and alteration have caused chlorite and sericite to be the predominant minerals. For these reasons feldspar plays a negative role as an ore indicator;

that is, where large quantities of fresh feldspar are found in the Cedar Bay area, probably ore is not nearby.

CONCLUSIONS

The most noteworthy feature of the alteration map (Fig. 5) is the arrangement of the alteration zones parallel to the ore zones. The main alteration zone strikes northwest-southeast as do the main sulfide veins. Near the center of the map the alteration zones branch to the west as do the veins.

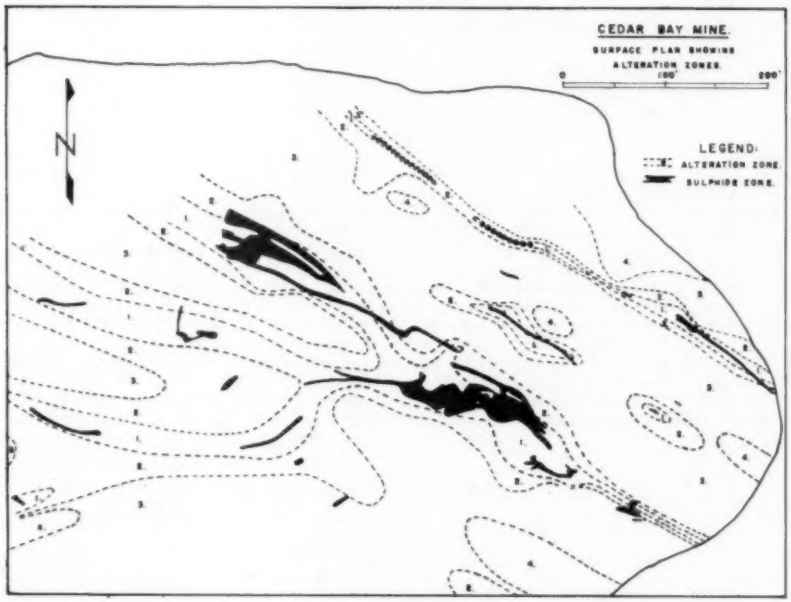

FIG. 5. Plan map of alteration and sulfide zones. Note the parallelism between the alteration and sulfide zones.

A quantitative aspect may also be noted. The wider alteration zones showing near ore alteration (zones 1 and 2) contain the larger veins. In other words, the thickness of the wall-rock alteration zone varies directly as the thickness of the ore shoots.

The value of using alteration zones is apparent. With this method, a much larger target may be sought than merely using the veins. Where the ore bodies have a lenticular habit, alteration zones may become ore zones along strike. Other applications under various conditions may certainly be found.

Although the microscope was used extensively in making this classification,

megascopic examination by a geologist or trained prospector should be very valuable in estimating the proximity of specimens to ore deposits.

ACKNOWLEDGMENTS

The writer is indebted to Dr. F. F. Osborne, who was a source of information and encouragement during this study, and to the other members of the Geology Department of Laval University who were also generous in their assistance. Dr. S. E. Malouf and other members of the Campbell-Chibougamau Mines Limited staff freely contributed ideas and other help. The president and directors of this mining company are hereby thanked for granting permission to publish this information.

NORANDA MINES LTD.,
NORANDA, QUEBEC,
May 25, 1960

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PALEOZOIC BANDED IRON-FORMATIONS

J. E. O'ROURKE

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ABSTRACT

Prospecting in the Nepál Himálaya has brought to light iron-formations that are probably Paleozoic, and a search of the literature has revealed others. The generalization that all iron-formations are Proterozoic or Archeozoic, which is a basic assumption in many theories, is very probably not valid, therefore. A class of iron ores intermediate in lithology and age between the banded iron-formations and the Clinton ores is described. A factor that may explain the distinctive features of banded iron-formations while accounting for the absence of these features in the Clinton ores is discussed. The suggestion is made that sedimentary iron ores show a progressive change in lithology with tectonic evolution.

INTRODUCTION

BANDED iron-formations have been considered, for many years, a phenomenon peculiar to the Archeozoic and Proterozoic eras, and special theories have been proposed to explain their supposed absence from the younger eras. Noting, therefore, that the newly discovered iron-formations of Nepál are

probably Paleozoic, and being familiar previously with the Mato Grosso deposits, also considered Paleozoic, the author was moved to inquire why iron-formation is thought to be restricted to the older eras.

A search of the literature revealed several other examples that are probably Paleozoic, as well as a large group of deposits that do not fit the strictest definition of iron-formation,[1] but may be transitional types. Probably only one of these examples can be regarded as completely "proved," but some of the others have a high degree of probability. The reader may judge this for himself from the quotations cited. Many of these were written in languages other than English, but the writer has translated them as literally as possible.

The field work on which the descriptions of the Nepáli occurrences is based was performed in 1957–58–59, while the author was engaged by the International Cooperation Administration of the United States government. Research and writing of the report was done subsequently, on private time. The objective of the mineral exploration program in Nepál was to find deposits of exportable ores, and time was devoted to iron deposits only after this objective had been accomplished. Therefore the detailed stratigraphic studies necessary to establish the iron-formations as Paleozoic could not be made, but sufficient data were collected to show that they are probably that age. Exploration continues, and the Nepáli geologists will carry on the investigation of this problem.

ACKNOWLEDGMENTS

Information and publications on certain districts were kindly provided by B. E. Ashley, U. S. Bureau of Mines; O. Barbosa, Universidade de São Paulo; J. E. Gilbert, Quebec Department of Mines; G. A. Gross, Geological Survey of Canada; H. D. Pallister, Geological Survey of Alabama; and D. Tadeu, Servícios Geológicos de Portugál.

G. R. Richardson, present Minerals Advisor to the government of Nepál, kindly sent specimens and a chemical analysis of ore obtained by recent drilling on the Phulchoki prospect.

H. L. James, of the U. S. Geological Survey, read the manuscript and made several valuable suggestions on its presentation.

EXAMPLES OF PALEOZOIC(?) IRON-FORMATION

The Himálayas of Nepál, Kashmir, and India.—Iron-formations appear to be numerous along a 1600 km sector of the Himálaya mountains from Kashmir to Bhutan. (Fig. 1) Those in Nepál are new discoveries not previously mentioned in the literature.[2] The others have been known for

[1] The term iron-formation is used in this report only for sedimentary iron-ores that show alternating bands of iron minerals and cryptocrystalline silica (or "chert"). For additional emphasis, the qualifications "*banded* iron-formations" and "*conventional* iron-formations" are applied to the same rock. Definitions of other iron ore types are summarized in Table 3. The term "ore" does not have economic connotations in the present usage.

[2] Additional information on the setting of the Nepalese deposits will be presented in a report now nearing completion (50).

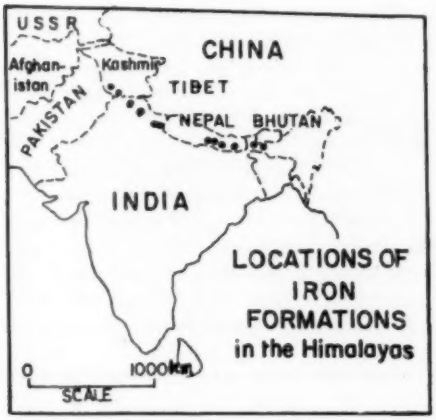

FIG. 1.

many years, but, with one exception, have not been described in detail, and have not been recognized as iron-formation.

Nepál—The iron deposits of Mount Phulchoki are located at Latitude 27°23′ N, Longitude 85°23′ E, about 13 km southeast of Kathmandu (Fig. 2). Discovered by the Nepal-American Minerals Co-operative Service in 1953 (64), they have been mapped in detail, connected to the capital by road, and explored at depth by diamond drill. The main ore zone is about 20 m thick and has been followed, by trenches, for about 900 m. The associated sediments are arranged in the following sequence: basal orthoquartzite; siltstone; iron-formation; and dolomite, with minor lenses of iron-formation and slate (Fig. 3). This group is underlain by a unit of massive dolomite several hundred meters thick.

Two types of sedimentary iron ore comprise the main ore zone: one is composed of alternating laminae of hematite, jasper, and silt; the other con-

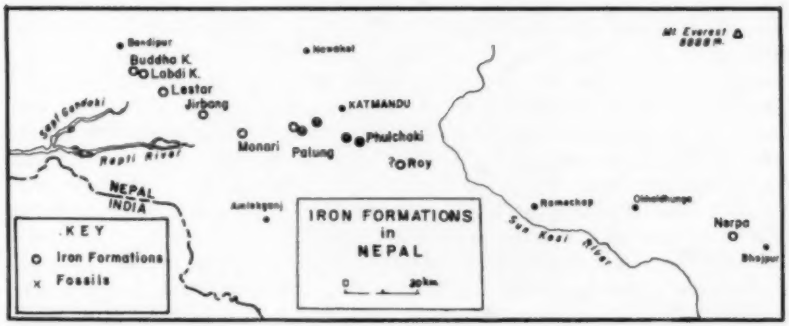

FIG. 2.

sists of pisolites of hematite in a matrix of hematite, calcite, and quartz. The laminated ore is tough and compact and forms resistant outcrops. The lamination results from a sharp differentiation of iron and silica components, and from slight differences in the color and texture of the hematite. The iron-rich layers, composed almost entirely of dense, finely crystalline hematite, range in thickness up to 2 cm and in length up to 20 cm. The jasper occurs as nodules and as laminae up to 3 mm thick and up to 10 cm long. It is typically bright red except in places where it has recrystallized to very fine quartz. The silt layers are thin wisps a few millimeters thick, although near the bottom contact they are several tens of centimeters thick.

The banded ore is much richer than typical iron-formation: 13 channel samples range in iron content from 54 to 60 percent and average 56.5 percent (64). The high grade may be ascribed in part to supergene enrichment,

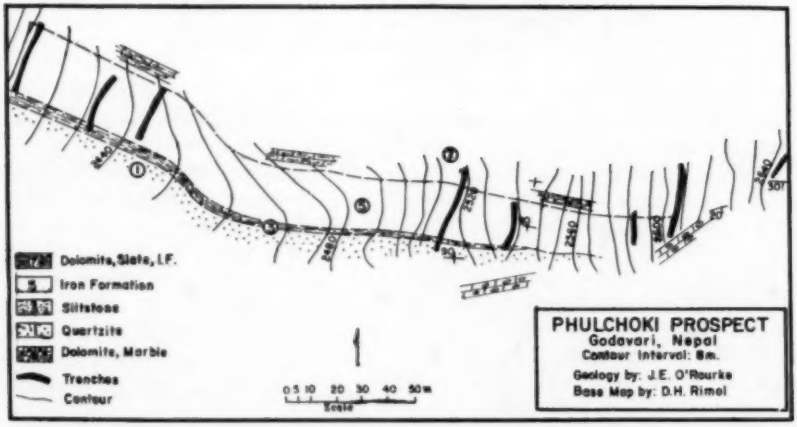

FIG. 3.

since the ore shows tiny vugs, microcolloform structure, and replacement between iron and silica bands, but enrichment probably resulted more from addition of iron than subtraction of silica, because the ore is massive and compact rather than earthy and friable. Certainly weathering has been intense on Mount Phulchoki, which receives an estimated 250 cm of rain during the four-month monsoon, and is subject to freezing temperatures during much of the dry season. On the other hand, the high tenor of the ore does not necessarily imply large scale enrichment, because many of those sedimentary iron deposits described in this report that are not conventional iron-formations also average + 50% Fe (Table 2). Comparison of chemical analyses of ore from the surface with ore from 15 m depth (Table 1) shows little difference in grade, but the limit of weathering has not been reached. Drilling has been suspended now, and it may be some time before the mineralogy of the completely unweathered ore is known.

TABLE 1

CHEMICAL ANALYSES OF BANDED IRON ORE FROM THE PHULCHOKI PROSPECT, NEPAL

	At Surface*		At 15m Depth**
Fe_2O_3	79.24%		78.25%
FeO	4.32		2.93
SiO_2	10.25		14.02
Al_2O_3	4.08		1.50
CaO	nil		trace
MgO	0.70		0.69
Mn	0.06		(MnO)0.02
P	0.04		(P_2O_5)0.13
S	nil		trace
TiO_2	ND		0.10
H_2O	1.19		2.04
"Alkalies, etc."	ND		0.32
Total	99.82%	Total	100.00%
	(Total Iron = 58.8%)		(Total Iron = 57.0%)

* From field report by P. B. Malla (34).
** From personal communication by G. R. Richardson, 1960.

The pisolitic type of ore, which is enclosed in the banded ore as lenses up to 2 m thick and 20 m long (Fig. 4), is composed of variable proportions of hematite, calcite, quartz, and clay (Fig. 5). The hematite is a dull red color, but is very finely crystalline under the microscope. The quartz of the pisolites forms thin concentric layers and probably represents recrystallized chert. The quartz of the matrix appears as fine, slightly rounded grains,

FIG. 4. Iron ore, Phulchoki Nepal. Leached oolitic ore, (under hammer) interbedded with banded ore. Photo by author.

and is probably of detrital origin. Calcite constitutes as much as half the bulk of the matrix, but is rarely found in the pisolites. In some of them, however, it forms a solid core several millimeters in diameter. Many pisolites have no cores or nuclei and are made up almost entirely of hematite, but most of them contain both hematite and quartz, and have, as a nucleus, a single rhomb of iron carbonate. The pisolites reach an extreme diameter of 40 mm, but average about 5 mm. Spherical, ellipsoidal, and elongate forms are about equally abundant, and occur mixed together.

Fossils are scattered through the pisolitic ore, and are so numerous in some portions as to constitute a ferruginous coquina. (In contrast, the banded ore is apparently unfossiliferous, even where it encloses lenses of fossil-rich ore.) Brachiopods, cephalopods, trilobites, and echinoderm stem-fragments are the chief forms (Figs. 6, 7). They are represented by casts-and-molds, with a thin film of hematite in place of the shell. Some of the stem-fragments retain their original calcite, but most of them have also been replaced by hematite. Identity of the fossils is discussed below.

FIG. 5. Iron ore, Phulchoki, Nepal. Oolitic variety; oolites of hematite in matrix of hematite, calcite, and quartz. Photo by Ganesha Man.

The pisolitic ore is very susceptible to weathering, and is generally in a highly leached condition. The original grade is difficult to estimate, but judging from the few unaltered specimens obtained, even the calcitic ore probably has more than 35 percent iron. Thus the pisolitic, fossiliferous ore of the Phulchoki prospect is very similar to the Clinton-type ore of the Appalachians, except that it is probably richer.

The other Nepalese deposits, all new discoveries, are aligned in a belt about 70 km long stretching westward from Phulchoki (Fig. 2). They appear to be spaced at intervals of 10 to 15 km on the map because they have been found by tracing float, and some of them have not been explored in the rugged interstream areas. No doubt they are more nearly continuous.

These ores are more highly metamorphosed than those of Phulchoki, since they occur in a zone of intense shearing related to thrust faults. They are composed of alternating bands of specularite and very fine quartz (recrystallized chert) with minor amounts of magnetite (Figs. 8, 9). They are, in other words, typical iron-formations like those of peninsular India, or Minas

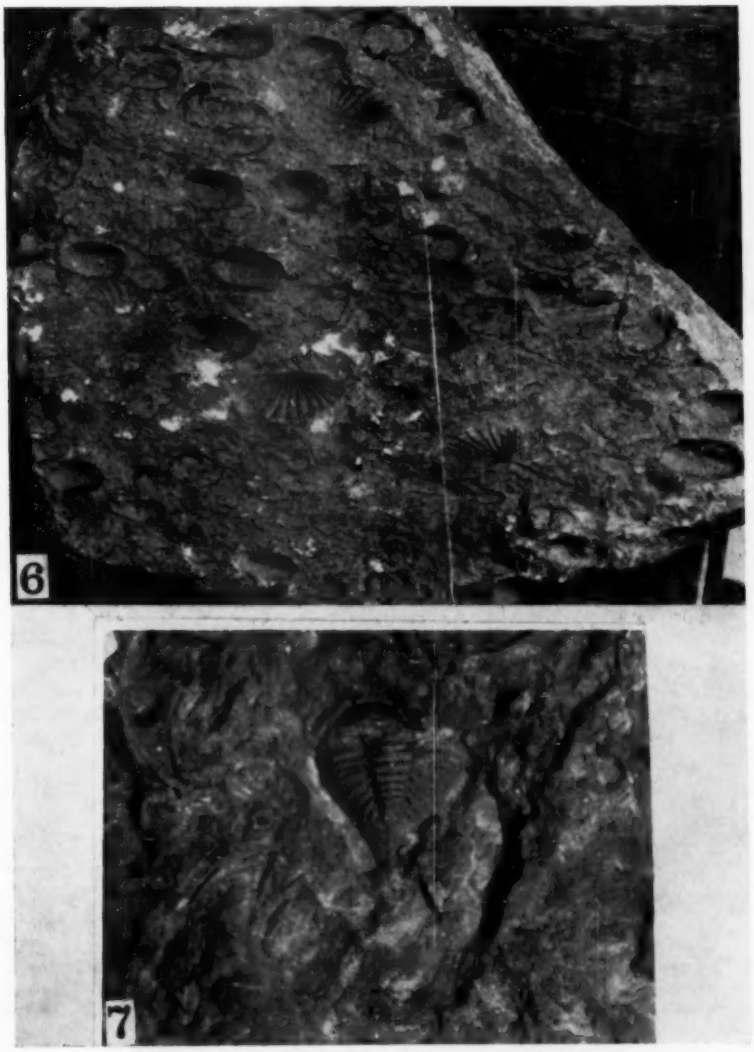

FIG. 6. Fossils, Phulchoki, Nepal. Brachiopods in dolomite of Zone 7. Photo by Ganesha Man.

FIG. 7. Fossils, Phulchoki, Nepal. Imprint of trilobite in iron ore. Photo by D. N. Rimal.

FIG. 8. Banded iron-formation, Buddha Khola, Nepal. Alternating bands of iron-oxide and recrystallized chert. Specimen comes from bed under pencil in Fig. 9.

FIG. 9. Banded iron-formation, Buddha Khola, Nepal. Transition-zone above the bed of iron-formation is composed of alternating bands of iron-oxide, (black) dolomite (white) and slate. Photo by author.

Gerais. The largest deposit, at Labdi Khola (49) contains several million tons of material running 30 to 65 percent iron. The prospect has not been mapped in detail, but is known to comprise several ore zones with a total thickness of 200 m. Banded iron-formation, "blue dust ore," hard massive hematite, and other ore-types are interbedded with gray phyllite and massive dolomite, but the overall sequence is quartzite, phyllite, iron-formation, dolomite, as at Phulchoki.

The deposit at Nerpa, in eastern Nepal, represents iron formation in a still higher zone of metamorphism, near the Sikkim gneiss. The ore, which occurs in a bed 2 to 3 m thick, enclosed in dark gray phyllite, is composed of alternating bands of magnetite and a yellow ocher pseudomorphous after a tabular mineral, presumably an iron silicate. A similar deposit in the Darjeeling district of India is cited below.

Kashmir—Deposits of iron ore that may be iron-formation have been reported from the so-called "Agglomeratic-slate series" which is said to contain fossils dated Carboniferous (39):

> A thick deposit of iron ore is found at the foot of a steep slope leading to Khandli Devi, west-north-west of Gagrot village (33°26′ N, 74°28′ E). It occurs at the base of the quartzite scarp overlying the Agglomeratic slate series. . . . The ore is hematite occurring in two beds, the lower one being (1.5 to 3.4 m) and occasionally up to (6.5 m) thick, while the upper one is (0.65 to 1 m) thick. The two beds are separated by (1.5 m) of ferruginous cherty rock. The ore forms a series of irregular bands in these two beds and includes different varieties —some hard and compact, some micaceous and others specular or granular. The approximate quantity in these two beds is of the order of 5 million tons . . . (29).[3]

Himachal Pradesh—The deposits of the Mandi district said to comprise two types of "itabirite": one is specularite schist, the other "consists of alternate layers of magnetite and micaceous hematite, and is profusely dotted with grains of magnetite and quartz" (57). Only the high-grade facies of the deposits have been described, and the authors would restrict the term "itabirite" to these portions, but they imply, in their theoretical discussion, that these ores grade into banded quartz-magnetite-specularite schist. Reserves are said to be on the order of 10^7 tons of material running + 35% Fe. The associated slates are said to belong to the Krol series, the age of which is discussed below.

Uttar Pradesh—The deposits of this state, which borders Nepal on the west, are known only through notes in the old literature:

> I may mention the vicinity of Ramgarh in Kumaon, Shele east of Simla, and Kohad in Chota Bangahal. The ores are magnetic and micaceous iron; they appeared to me to be metamorphic deposits, and are probably more or less strictly representative of each other throughout the middle zone of the lower Himalaya (37).
>
> Ramgarh—Several bands of micaceous hematite, varying in thickness up to (3 or 4 m), one of which has been traced for a distance of (ten km). The ores are associated with talcose and clay slates (29).
>
> Dhaniakot—The ores are usually specular or micaceous hematite occurring in calcareous slates with thick beds of quartz (30).

[3] The original data come from a report (40) that is not available in the United States.

West Bengal—The deposits near Darjeeling are highly metamorphosed, like those in nearby eastern Nepal:

> A valuable bed of iron-ore was discovered about (two km) east-south-east of Sikbhar. . . . The ore bed is about (seven m) thick and is associated with quartz-schist, talc schist, and actinolite rock. In places the ore is pure magnetite, but more usually it includes a varying proportion of actinolite. At the spot where the ore has been worked, it is a schist, composed of magnetite, micaceous hematite, actinolite, and talc, irregularly interbanded; the last three also including octahedrons of magnetite. Specimens of both kinds of ore have been assayed by Mr. Tween, with the following results: Magnetite—71.5% iron; Micaceous hematite—58.9% iron. Neither contains any phosphorus or sulphur." "Blocks of magnetic-iron schist are washed down by the Sakkam river south of Dalingkot." "The Ma-Chu brings down large lumps of micaceous hematite (35).

The Duars—The deposits of the western Duars of India and Bhutan occur in the Baxa series, which is Permo-Triassic(?):

> There is a rock (as in the Raimatáng naddi) amongst the impure calcareous beds of the series, which consists of interbanded layers of dolomite, red jasper, and thin seams of micaceous iron, and including besides irregular seam-like nests of quartz mixed with sericite. The rock varies from one in which the dolomite and jasper are interbedded in regular layers (6 to 13 mm) thick or more, to an impure dolomite merely containing seams and nests of jasper, etc (35).

Data are not yet sufficient to correlate and date the numerous Himálayan deposits, but it seems likely that some of them, at least, are Paleozoic. Fossils in the ores at Phulchoki include brachiopods, cephalopods, trilobites, and echinoderm stem-fragments, nearly all of which are poorly preserved. Several good specimens were found, however, when the trenches were dug in 1954 and 1955. They were collected and studied by D. N. Rimal (56). He identified *Orthis*, *Orthoceras*, and *Phacops rana*(?) (Figs. 6, 7). The trilobite is of course, a world index-fossil for the Devonian, but the other forms seem more typical of earlier periods. In any case, the ores are definitely Paleozoic. Unfortunately, the associated banded ores are too rich to be considered iron formation in the strictest sense, even though they are very similar to the unmetamorphosed Mato Grosso ores noted below. The other deposits in Nepal, though definitely banded iron-formation, cannot be dated so conclusively. They are however, closely associated with a fossiliferous dolomite, a massive unit several hundred meters thick that apparently underlies all of them.

The typical dolomite is white or gray, coarse grained, highly fractured, and cut by veinlets of quartz, dolomite, and siderite. A minor purple facies rich in fossil fragments has been quarried at the base of Phulchoki and used to decorate the royal palaces in Kathmandu. Its fossils include brachiopods, cephalopods, corals, algae, and echinoderm stem fragments. A genera of Archeocyathides (Tabulacyathus?) is considered of Cambrian age (11). Fossils found in the dolomite at Chandragiri Pass, on the main trail south of Kathmandu, include brachiopods, (Orthis?) cystoids, and bryozoa(?) considered possibly Ordovician (5). A hexacorral found in the dolomite north of Palung is an advanced type, lacking in epithecal walls, which would

indicate a still younger age.[4] Fossils have not yet been found in the dolomite that underlies the remaining deposits to the west in the zone of higher metamorphism. Significantly, however, the two deposits at the end of the belt, Labdi Khola and Buddha Khola, are contained in a group of sediments very similar to those at Phulchoki, and arranged in the same sequence: coarse clastics, fine clastics, iron-formation, dolomite, the whole group being underlain by a unit of dolomite several hundred meters thick.

Correlation of these rocks was first suggested by Medlicott (38), who noted that the dolomite and clastics near Bhainse Dhoban are very similar to those near Kathmandu and Phulchoki. He suggested that they were the same units repeated by faulting, and correlated them with his Krol series.[5] Recent work by Bordet and Latreille (11) tends to confirm this observation by showing that the rocks of this zone in eastern Nepal are Paleozoic sediments repeated "a score of times" by faulting. Since none of these investigators were aware of the iron-formations near the front of the Himálaya; near Kathmandu; and near the type section of the Krol, the probability of the correlation is even more likely. Complete proof would necessitate mapping the entire stretch of rugged country between the fossiliferous Phulchoki deposits and the metamorphosed iron-formations, or at least finding fossils a little closer to the latter. Until this work has been done, the Paleozoic age of the iron-formations should be considered tentative because of the serious implications involved in correlating typical banded iron-formations with deposits containing a facies of typical Clinton ore.

The Mato Grosso Region of Brazil and Bolivia.—The principal iron-ore deposits of the Mato Grosso are found in the basin of the Rio Paraguaí, near Corumbá in Brazil and Mutun in Bolivia. They are large (10^{10} tons) and rich (+ 50% Fe), but are so remote that they would have received little attention except for the valuable deposits of manganese associated with them. Development work has centered around Morro d'Urucum, one of several ore-bearing mesas near Corumbá.

The iron-formation, virtually unmetamorphosed, is composed of alternating laminae of hematite and jasper (Fig. 10). The hematite is dense and very finely crystalline; it has a red-gray color. The jasper is generally pure, but in places contains very thin streaks of gray hematite. It is typically bright red. As indicated by the tenor, jasper is not so abundant as in most iron-formations, and some ore beds up to ten meters thick are nearly free of it (3). Also, the jasper bands are not so regular and persistent as those of hematite:

> The laminae of hematite, in general with a uniform thickness of 0.5 to 2 cm, are constituted of papery sheets that in cross-section are differentiated through

[4] This specimen was shown to the author by two men of the village. They maintain it is a manifestation of a certain well-known diety (presumably His Footprint), and would not sell it, lend it to be photographed, or reveal its exact provenience.

[5] The Krol was first considered Permo-Triassic, then lower Paleozoic or upper Proterozoic, but is now dated Permo-Triassic by most geologists. Inquiries at press time indicate that many Himálayan iron deposits are Carboniferous to Permo-Triassic, and the Labdi Khola occurrences may perhaps be correlated with them rather than with the lower Paleozoic Phulchoki group.

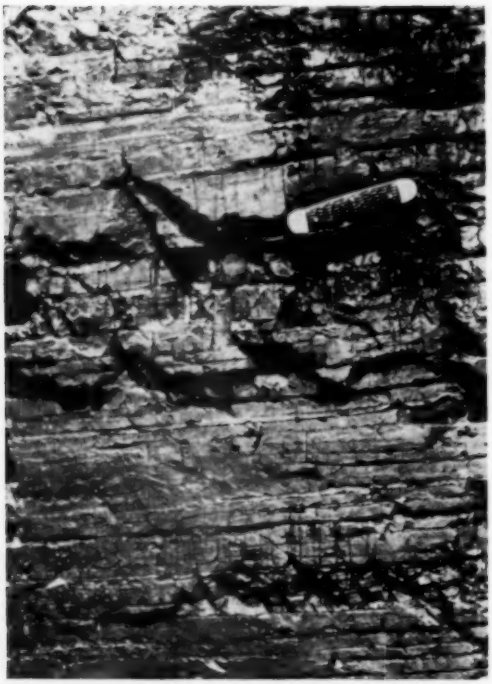

FIG. 10. Banded iron-formation, Morro do Urucum, Mato Grosso, Brazil. Typical ore with alternating bands of hematite and jasper. Photo by author.

luster. They are regular, with a certain horizontal persistence, but this is not the case with those of jasper, which are present as discontinuous laminae or in forms lenticular, ellipsoidal, or nearly spherical. Locally, thin laminae of jasper may "balloon" (*infletem-se*) to become nodules. The laminae of hematite, formed of very fine-grained material, are flexed upward and downward, molding themselves to the irregularities of the jaspilitic structures, but without suffering any noticeable thinning. (Translated from the Portuguese.) (3).

Parts of the iron-formation are oolitic or pisolitic. These structures are generally massive, but may show concentric banding: few, if any, have nuclei (3). The presence of an oolitic facies, the high tenor, the comparative lack of cryptocrystalline silica, and the overall megascopic appearance of the iron-formation are points of similarity with the deposits at Phulchoki, Nepal.

The Mato Grosso iron deposits are part of the Jacadigo series, an integral group of sediments that shows the following sequence: arkosic sandstone, siltstone, ferruginous jasper, and iron-formation. These components are said to have gradational contacts, and correspond to the zones of coarse clastics, fine clastics, and iron-formation noted in Nepal and elsewhere (50). Dolomite is not present, but then the top of the sequence apparently has not

been preserved in any of the mesas. The remnant iron-formation is between 300 and 400 m thick, and includes two extensive beds of high-grade manganese ore, as well as minor lenses of clastics.

The Jacadigo series is horizontal and rest unconformably on sub-horizontal or slightly folded sedimentary rocks of the Bodoquena and Corumbá series, or directly on igneous and metamorphic rocks of the "basement complex." The basal conglomerate of the Jacadigo contains large boulders of granite, dolomite, and other rocks representing all the older assemblages. Thus the relative age of the iron-formations is well established (3).

Several kinds of structures that may be organic have been found in the iron-formation, but none have been identified.[6] Fossil algae have been discovered (7) and described (9) recently from the underlying Corumbá limestones. They are classified as new species of the genus *Aulophycus*, which is said to be associated with middle and upper Cambrian rocks in the northern Rocky Mountains. Reservations have been expressed about applying a similar age to the Corumbá series because the stratigraphic range of the genus apparently has not been fixed, and may conceivably extend into the upper Proterozoic. Even so, the presence of such fossils in the Corumbá is strong evidence of a Paleozoic age for the iron-formation of the Jacadigo series, which overlies the Corumbá unconformably. Furthermore, Cambrian species of *Collenia* have since been reported, though not described, from these limestones.[7]

The Malyi Khingan District, Dálnii Vostók, USSR.—This iron range is said to extend for more than a thousand kilometers through the so-called "Far East Region" of the USSR and across the Amur River into Manchuria. Exploration on the Soviet side of the border has been confined mostly to the Malyi Khingan district.

The deposits of the southern part of the district are "hematitic hornstones" (*hematitovye rogoviki*) composed of alternating bands of hematite and chert ranging in thickness from 0.2 to 10 cm (15). Deposits in the northern part of the district are locally metamorphosed to ores composed of specularite, magnetite, martite, and cummingtonite, with quartz or, in places, dolomite. Both types are about the same grade (33% Fe), but the metamorphosed variety is much more amenable to beneficiation. Reserve estimates run as high as 10^{10} tons.

The Malyi Khingan ores have been recognized as standard iron-formation and are often compared with the well-known deposits at Krivoi Rog:

> They are the banded type, consisting of alternating, ideally parallel layers of ore and gangue ranging from very thin to more or less thick. The barren layers are siliceous schist; the ore layers, depending on the degree of metamorphism,

[6] In the cited paper, Professor deAlmeida says that some structures in the iron-formation at Mutun, found by F. Ahlfeld, were sent to the U. S. Geological Survey for identification. Eight paleontologists examined the specimens: six pronounced them inorganic, but two said they might be altered *Girvanella*, a genus of algae common to many Gothlandian iron ores in Europe.

[7] In a personal communication, Professor Barbosa alludes to additional evidence, and says the iron-formation is "without doubt" (sem dúvida) Paleozoic, perhaps Ordovician or "Silurian."

consist either of hematite or magnetite, with variable amounts of siliceous matter. The thickness of the individual ore bands varies from less than a millimeter up to 5–10 cm, reaching in some cases up to several m or even more. The total thickness of the ore pack . . . varies from 10 to 30 m, most often it makes 10–12 m. (Translated from the Russian.) (43).

The associated sediments include sandstone, graphitic slate, dolomite, and limestone; the stratigraphic sequence has not been resolved. Dating is by fossils and lithologic correlation:

> The age of these strata . . . has been referred to the Cambrian conditionally. The stromatolith found by S. A. Muzylev shows the form typified problematically by the blue-green alga *Chlorellopsis Reis* analogous to certain species from Cataret, France, of Cambrian age described by A. Bigot. (Translated from the Russian.) (36).
>
> As concerns the age of the ores, this question is not quite clear. The algae found in the hanging wall of the ore-bearing zone, according to the determination by V. P. Maslov, most probably testify to a Cambrian age, but if we compare our strata with the southern Manchurian ones, with which they have many common features, then we will have to speak of a pre-Cambrian age, since in Manchuria, according to the geologist Murakami, the corresponding ore-zones are overlain by deposits containing well-preserved Cambrian fossils. Several stratigraphic comparisons . . . lead me to the thought that most probably these deposits relate to the lower Paleozoic. (Translated from the Russian.) (43).

But the evidence from the Manchurian occurrences supports, rather than vitiates this estimate of a Cambrian age, as shown below.

The An-Shan District of Manchuria.—The center of development of the Manchurian iron-ore belt is at An-Shan, about a hundred kilometers south of Mukden and more than a thousand kilometers south of the Malyi Khingan district just described.

Two iron-formations, of different ages are recognized (42). The one that contains mineable ore-bodies is called "hematite-quartz-schist" and is well-banded. This iron-formation is contained in a mass of highly folded and metamorphosed "green schists," tuffs, and graywackes that are known to be older than the Proterozoic Sinian System, and are believed to be Archeozoic (58).

The other iron-formation is called "ferruginous quartzite," but is said to be virtually indistinguishable from the "hematite-quartz-schist," except by its stratigraphic position (42). Its banding and notable lack of detritus show that it is not a clastic quartzite, as the name might imply. It resides in a group of sediments, dated lower and middle Cambrian by well-preserved trilobites, that shows the following sequence: basal conglomerate and orthoquartzite; siliceous slate; iron-formation; a zone of mixed marl, slate, and fine sandstone; and finally a thick, fossiliferous dolomitic limestone. Where the contacts are discussed, they are said to be gradational, and it would seem that the group represents another example of transgressive overlap (50).

The apparent dilemma posed by the Malyi Khingan deposits, which show evidence of a Cambrian age, yet were thought to be an extension of the Archeozoic deposits of Manchuria, would be resolved if the existence of two distinct iron-formations were established in both districts. The lower

Cambrian is said to be extensively developed in this region (4), and the sediments associated with the Malyi Khingan ores seem, from the descriptions, to have much more in common with the well-differentiated Cambrian sediments at An-Shan than with the Archeozoic "green schist complex."

The Highlands of Arctic Norway.—These iron ore deposits form a belt about 500 km long between Trondhjem and Narvik, with the main prospects centered around Dunderlandsdal on the Arctic Circle. They contain about 10^8 tons of material running 33% Fe. The ore is a specularite-quartz schist, locally well-banded (Fig. 11). Some authors have pointed out that the bands are not quite so regular and persistent as in ideal iron-formation, yet they are as much as 10 cm thick and 30 cm long (70). Parts of the ore contain

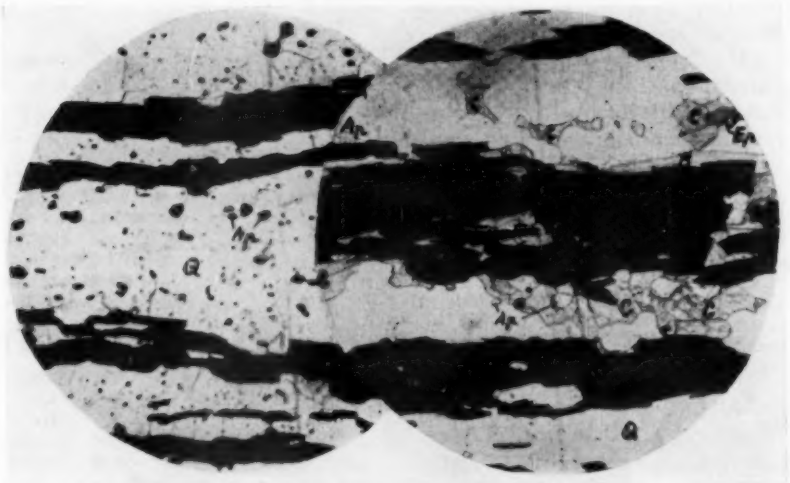

FIG. 11. Banded iron-formation, Rana, Norway. Symbols: O = iron oxide; Q = quartz; C = calcite; Ap = apatite; Ep = epidote; Scale: × 50. Photo by Bugge (12).

minor amounts of magnetite and small percentages of epidote, garnet, and other metamorphic minerals. The ore beds are several in number and range in thickness up to 50 meters. They are interbedded with schist and closely associated with dolomitic marble.

These iron-formations have been described in several major publications: of six consulted, five discuss the age, and conclude that it is probably "Cambro-Silurian." The reasons are as follows: the deposits are not part of the Scandinavian Shield, but belong to the *fjellformasjon,* a major rock sequence and tectonic zone that extends down the coast of Norway and across the North Sea to the Scottish Highlands. More specifically, they are contained in the "Nordlands schist-marble group," which has been dated with fossils at several places (71).

A recent paper on the Dunderlandsdal says:

> The sedimentary series belongs to the lower part of the highland sediments. We do not yet have a certain age determination because fossils have not yet been found, but after the work of Th. Vogt (72) in the Sulitjelma area, an upper Cambrian to lower Ordovician age is probable. The lithology can be correlated with the lower sediment series in the Sulitjelma area (Fauske limestone, Muorki schist, etc.) which is overlain by the Sulitjelma schist where that contains middle Ordovician fossils. (Translated from the Norwegian.) (12).

The Tras-os-Montes Region of Portugal.—The three principal iron districts of northeastern Portugal are: Vila Cova, located about a hundred kilometers east of Porto; Moncorvo, about 200 km east of Porto; and Guadramil, in the northeastern corner of the country, astride the Spanish frontier. All three occurrences are dated with fossils and are thought to belong to the some epoch of the Ordovician (14).

The Moncorvo deposits appear to be the largest, with some 10^8 tons of material running 45–55% Fe. They comprise several beds of ore 1 to 8 m thick interlayered with slate and associated with micaceous quartzite. Two varieties of primary ore are recognized:

> The first and most abundant ore is the hard micaceous type . . . its structure is very slaty, a property determined by the abundance of folia of specularite and some sericite that produce *lisos* or parallel planes of easy separation; in some cases they are divided into bands 1 to 3 cm thick. These ores . . . also contain remnants of micaceous sandstones . . . which sometimes are present in the form of nuclei and sometimes in more elongate laminae that also facilitate the separation into brilliant *lisos*. . . . The other class of ore is . . . less siliceous and finer grained; this one, which is also richer, is in general less micaceous and slaty, perhaps for the very reason of having less quartz. (Translated from the Spanish.) (60).

Later mineragraphic work also distinguished two types of primary ore:

> The first type has a blue-gray color, a metallic luster, a micaceous and schistose aspect; the color of the streak is deep red-brown. . . . The second type has a black color, a fine-grained aspect, with a submetallic luster. The streak has a dark brown color. The fracture is conchoidal . . . in the first type specularite predominates; in the second, it is the martite. . . . The specularite ore as well as the martitic-specularitic ore has a grade of iron equal or greater than 50%. . . . The specularitic ore always shows (*zones remplies de ponctuations*), light blue-gray, elongated in the plane of schistosity, and sometimes taking the form of small flattened nodules, with a length of 3 to 5 cm. These inclusions are essentially composed of quartz and sericite. (Translated from the French.) (65).

The nature of the banding and lenses mentioned in these papers is not clear. Banding is shown in the only photograph of the ore that could be located (Fig. 12), but it is not the very regular, sharply differentiated type generally associated with iron-formation. The Vila Cova ores are said to be well-laminated, and to occur, not in massive beds, but as banded *complexos:*

> At least three complexes of magnetitic formations are recognizable. Each complex is constituted of numerous, narrow layers of magnetite, each one 3 to 35 cm thick, that alternate with fine bands of chloritic schists and quartzites, into which they grade laterally. The thickness of each complex varies from 1 to 8 m. (Translated from the Portuguese.) (13).

These ores cannot be considered conventional iron-formation, however, because the quartz is said to be detrital. To what existing class of sedimentary iron deposit do they belong, then? Some writers (14), noting that the Vila Cova and Moncorvo ores contain relict oolites, suggest that they may be the metamorphosed equivalents of the Guadramil ores, which are composed of oolites of siderite and silex in a matrix of siderite, calcite, and quartz (22). The associated sediments are similar, except that the slates at

FIG. 12. Banded iron ore, Moncorvo, Portugal. Alternating bands of specularite and quartz. Photo by Sampelayo (60).

Guadramil are graphitic, which has led to the modified theory (65) that the Guadramil deposits were formed under reducing conditions, while the Moncorvo ores, which contain fossils of the littoral zone, were deposited under oxidizing conditions. The possibility remains to be investigated that these three districts represent three stages of a facies gradation from oolitic ores of the Clinton type to banded iron-formations of the Lake Superior type.

The Kayes District of West Africa.—Sedimentary iron ores that may or may not be conventional iron-formation have been reported from several places in the Kayes-Est and Kayes-Ouest quadrangles of the "Sudan" in western Africa. The approximate center of the district is Lat. 15° N, Long. 10° W, about 800 km west-south-west of Timbuctu.

The ore is described thus:

> Another ferruginous horizon . . . occurs in the Ordovician sandstones. It is a case of schistose[9] hematites associated with bright red jaspers. . . . These hematites are present in small, horizontal, superimposed beds alternating irregularly with those of red ferruginous jasper, with argillaceous, brown, slightly ferruginous schists called chocolate schists; and with diverse gray or brown, more or less ferruginous sandstones. The whole group, which is apparently lenticular in the midst of the Ordovician sandstones, might have about 15 to 30 ms thickness. The ore ranges from 45 to 50% Fe and 20 to 25% SiO_2. . . . (Translated from the French.) (8).

These deposits are said to be part of a series of lower Paleozoic sediments —conglomerates, sandstones, "schistes," and dolomite—that can be followed from Guinea to Algeria. Fossils have been found at many places in this series, but not in the immediate vicinity of the iron ore deposits. These rocks are horizontal and rest "with slight discordance" on the horizontal or slightly folded rocks of the "Intermediate Series," which are generally considered Proterozoic because they lack fossils. The "Intermediate Series" rests, in turn, on the igneous and metamorphic rocks of the "ancient shield." It is interesting to compare the stratigraphy and ore lithology of these deposits with those of the Mato Grosso.

The Santo Leone District of Sardinia.—The banded quartz-magnetite deposits of the Gothlandian (41) rocks at Santo Leone, in the Sulcis district of southwestern Sardinia may or may not be iron-formation. Most contemporary writers regard them as pneumatolytic replacements of limestone, but an early investigator presented evidence for a sedimentary origin (16). The ores, running 40–65% Fe, consist of alternating bands of magnetite and quartz with variable amounts of garnet, epidote, hedenbergite, and other metamorphic minerals. The description of the structure of the ore seems significant:

> The quartz is present in small beds of one or two centimeters thickness. These small quartzose beds are remarkable for their regularity and for their arrangement parallel to the stratification of the ore bed (Translated from the French.) (16).

On the other hand:

> The widespread diffusion of garnets with amphiboles, pyroxenes, and epidote; the existence elsewhere in the region of lower Paleozoics formed of extensive

[9] The literal translation of "schisteuses" is given here, although the rocks are apparently not metamorphosed. Probably "shaly" is meant. The French *schiste*, Italian *scisto*, Swedish and Norwegian *skifer*, German *Schiefer*, and Russian *shifer*, all derived through the Latin *schistus* and Greek σχιστός from the Indo-European root *skhid-* (to split) are often used ambiguously for any lamellar rock. Other languages require a consistent differentiation according to the metamorphic grade, as in the Portuguese *folhelho*, *piçarra*, *filito*, *schisto*, or the English *shale*, *slate*, *phyllite*, *schist*. The latter, however, lack a generic term to include all argillaceous rocks. An international terminology is needed.

masses of limestone enclosed in schists; the similarity of the deposit with Monte Lapanu, 25 km further west; leaves one to suppose the presence here of metamorphosed limestone, although it is not present (*in modo evidente*) outside the Assemini group of concessions. (Translated from the Italian.) (67).

Inasmuch as the evidence does not seem to favor either theory exclusively, an alternative suggests itself: perhaps pneumatolysis has been superimposed on a pre-existent iron-formation, as in the well-known deposits of central Sweden (20).

The Asturias Region of Spain.—Deposits of "itabirite" and "hematite-quartzite" are reported, in the old texts, from the Spanish provinces of Asturias, Leon, and Viscaya, but descriptions of them are scarce. A monograph on the iron ores of Asturias describes the Cambrian occurrences as follows:

> In some places of the Concejo de Coaña occur metamorphosed slates . . . alternating with hematite, it not being rare to find beds constituted by thin folia of schistose chlorite alternating with sheets of resinous hydroxide. Metamorphism has accentuated certain points near the intrusive rock; the hydroxide has become hematite—brilliant, specular, or scaly, and the rock affects the character of an itabirite.[10] To this type can be referred a bed of considerable thickness that is found near Villar, constituted of red hematite speckled with flakes of brilliant hematite, that affords a superb ore of extraordinary richness and good compactness; and there can be included also the red lamellar hematite of Boal, that originates, without doubt, from the transformation of a spathic carbonate and attains the following composition: Ferric oxide 91.7%, Alumina 4.5%, CaO + MgO 1.15%, SiO_2 0.4%, $H_2O + CO_2$ 1.55%. (Translated from the Spanish.) (2).

The Setolazar District of Morocco.—The deposits of the Setolazar district, located about 20 km southeast of the Mediterranean port of Melilla, are described as follows:

> The main ore is a sedimentary deposit. Hundreds of layers of more or less pure hematite are interbedded with shale or schist. The hematite beds vary in thickness from fractions of a millimeter to one or two meters. In places the stratification is so thin as to resemble a book. The thickness of this hematite series is over 50 m and perhaps over 100 m . . . (it) was followed by the writer for 2 km along strike and extends much further. The ore averages 50–54% iron (23).

The argillaceous rocks in the vicinity of the deposits are shown on the quadrangle maps (69) as "Silurian" with small patches of Jurassic. Fossils indicate "the Ordovician branch of the Silurian."

This ore is not conventional iron-formation, since it apparently lacks chert, but it has several points in common with some of the other deposits just described, and may perhaps represent a type of ore that is transitional between conventional iron-formation and the oolitic, siliceous iron ores that occur in the Ordovician at many places in central and western Morocco.

The Fleuve Rouge District of Tonkin.—Several iron ore deposits have been found along the Fleuve Rouge (or Red River or Song Koi) between

[10] The term "itabirite" originally referred to the hard, massive, dense, high-grade ore in the deposits of eastern Brazil, coming from the Tupi word for whetstone. It was later misapplied to include the iron-formation from which this high-grade ore is derived, and has since been used for everything from the banded jasper-hematite ores of the Mato Grosso to the taconites of the Lake Superior region. Some writers, as in this case, assume the term has a definite meaning, and employ it without ever describing the ore.

Laokay and Yenbay near the border of Tonkin and Red China: "There exists in this part of Indo-China, a veritable line of iron ore deposits about 80 km long, which is an ancient ferruginous sediment." (24).

The ores are called *quartzites à hematites* and *quartzites à magnetite*, but are likened to the well-known banded iron-formations at Stripa, Dunderlandsdal, and Krivoi Rog. They are described very briefly: ". . . one recognizes . . . magnetite layered with quartz, the two elements occurring alone and very pure, without other minerals except for very rare spangles of mica." (Translated.) (24).

The ore bed is 15 m thick and is associated with limestones and schists, the age of which has not yet been determined. An earlier paper on the stratigraphy (19) says that two time-rock units are present in the neighborhood: one belongs to the top (*le sommet*) of the "Algonkian," the other to the "Cambro-Silurian." Additional mapping would be needed to place the iron-formation in its proper context.

The Andes of Chile and Peru.—A Paleozoic banded iron-formation has been reported recently from southern Chile:

> The Relún deposit is in the Nahuelbuta range, about forty km from the coast, between Lake Llau-Llau and the River Relún. . . . It belongs to the sedimentary Lake Superior type and may be compared with the itabirites of Brazil and Venezuela. The ferruginous bed extends over an area of fifteen-by-eight km and is said to be twenty m thick. This bed appears between micacites of Paleozoic age (68).

The source of this information and the evidence for dating the rocks is not given.

The iron-formations of Peru are also newly discovered (18). They are located at Cerro Casca (or Tarpuy) about 80 km southwest of Arequipa. The ore consists of alternating laminae of hematite-magnetite and quartz, and is said to be "very similar to the itabirite" of Brazil. It runs 30–40% Fe. The deposits is 60 m thick and is surrounded by granitic gneiss. The age of these rocks is not known:

> The data at hand do not permit us to determine definitely the age of the Charcani gneiss, which only provisionally has been considered Paleozoic or Precambrian in attention to the fact that, in the region of Cerro Verde, it is found adjacent and apparently below the Chocolate volcanic formation of lower Jurassic age. (Translated from the Spanish.) (27).

The Appalachians of North America.—Clinton-type ores have received more attention than the other types of sedimentary iron deposits in the Appalachians, but ores that are either conventional iron-formations or a closely related variety have also been mentioned in the older literature. The following summary uses a regional grouping: 1) a belt of Cambrian deposits in the Valley-and-Ridge province of the southern United States; 2) a belt of deposits in the Paleozoic (?) rocks of the southern piedmont; 3) miscellaneous deposits in the Ordovician and Gothlandian of the northern United States and southeastern Canada.

Valley-and-Ridge Province—The largest and most productive of the

Cambrian deposits in the southern Appalachians are located near Talladega, Alabama, at the end of the mountain chain. The ores are called "gray ores" to differentiate them from the Clinton-type "red ores" and the residual "brown ores" of the region. They are composed of gray, metallic hematite and quartz with minor magnetite, and run 40 to 60% Fe. Two varieties are distinguished by physical properties: a) "hard, massive, quartzitic," and b) "soft, crumbly, and slaty" (63). The second variety is apparently banded: "The ore is sometimes massive in structure, sometimes laminated and almost fibrous, breaking up on weathering into fragments that resemble chips of wood" (62).

The deposits are said to be seams (0.65 to 2.6 m thick), associated with slates and quartzites of the upper part of the lower Weisner formation. This formation is the local representative of a well-known unit of marine clastics that marks the base of the Paleozoic for the entire length of the southern Appalachians (1).

The Cartersville district, located about 150 km to the northeast along strike, in Georgia, also has "gray ores" which are said to be interbedded with quartzites and slates of the Weisner formation (44) and with dolomite of the overlying Shady formation (28). Lower Cambrian fossils have been found in the ore itself (28).

Numerous small deposits of "hard, dense, specular ore of steel-blue color" are strung out along the Tennessee-North Carolina border in the Cambrian clastics, but only one of them was ever mined "to any extent" (59).

Sedimentary iron ore has been reported from the lower Cambrian Loudon formation at Mount Catoctin in Maryland. It is composed of magnetite and quartz and is said to assay 35% Fe and 34% SiO_2. The ore bed, which is 2 m thick and 5 km long, is "intercalated with and contained in, dark blue shale." The associated sediments are sandstones, shale, and limestone (61).

Piedmont Province—Deposits of "specular schist" and "magnetite schist" are numerous along the eastern slope of the Appalachians. Most of them were worked early and are known only through brief notes in resource surveys.

Alabama has deposits of "itabirite" in Clay county (51), and Georgia has deposits of "finely-banded magnetite schist" assaying + 60% Fe in Cherokee and Lumpkin counties (44). The South Carolina occurrences were world-famous a century ago, being cited in all the old texts as one of the first known examples of "itabirite." They are said to show many similarities with the iron-formations of Minas Gerais, including close association with "itacolumite," (31) and are said to be part of a nearly continuous iron ore belt that extends across North Carolina into Virginia (46). Another group of deposits, aligned with this belt, occurs in the Mt. Athos formation along the James River. Typical examples are described thus:

> (At Stapleton) The deposit is essentially a ferriferous slate and 'quartzite', approaching in character in some parts of the mine a pure specular ore. Thin layers of schist and 'quartzite' are found interlaminated with the ore. (At Riverside.) The ore is soft, specular, and contains occasional thin bands of hard fine granular hematite (54).

Two deposits of laminated magnetite-schist have been reported from Howard and Harford counties (61), and they apparently mark the end of the belt.

Traditionally, the rocks of the piedmont have been considered "Precambrian," but after repeated discoveries of fossils, some as young as Carboniferous (21), they are now regarded as largely Paleozoic. The apparent similarity of the piedmont ores with those of the Valley-and-Ridge province suggests the possibility that they might correlated, providing a much-needed marker horizon.

Northern Appalachians—The Sutton district of southeastern Quebec is located about 35 km east of the northern tip of Lake Champlain. The iron ore deposits were once widely cited as examples of "itabirite," but have never been described in detail. The original report says that they occur in slates of the Ordovician Quebec group (33).

A deposit near Brome is described thus: "The bed of ore, which lies in chloritic slate, is (1.5 m) in thickness, laminated in structure, and divided by thin layers of granular quartz and chloritic slate. The ore is dark purple-red in color and much richer in its aspect than most of those previously described" (33).

Later reports, all very brief, allude to "specular schist" and "hematite mixed with jasper bands," but also mention "veins of hematite" and "magnetite ore in serpentine," leaving the identity of the deposits in doubt (45).

The Bathurst district is located in northern New Brunswick at Chaleur Bay, the principal deposits being at Austin Brook, about 30 km south of the town of Bathurst. The oldest rocks in the area, slates and graywackes of the Tetagouche series, contain several species of Ordovician graptolites. The country rock exposed in the vicinity of the prospect is mostly "porphyry" said to be "post-Ordovician and pre-Devonian."

The iron ore deposits are described thus:

> . . . the mass thus has the appearance of a bed whose boundaries are conformable with the planes of schistosity in the surrounding rocks. The whole ore body has a very marked banded structure, parallel in dip and strike with the containing walls. The ore, as a rule, parts with some degree of readiness along planes also parallel to the walls. The banding varies in degree from microscopic to very broadly developed. . . . On the whole, the ore is composed of minute, rapidly alternating bands of nearly pure magnetite, or magnetite with considerable finely granular quartz, or feldspar or both minerals; and other bands of nearly pure quartz, or quartz with varying proportions of feldspar and magnetite, etc. (75).

Having described what seems to be a variety of iron-formation, the author draws a surprising conclusion: "Though the so-called quartz-porphyry may in reality be a tuff, there does not appear to be any ground for supposing the ore bodies to be of the nature of sediments or chemical precipitates, and if the quartz-porphyry is indeed a massive rock, it would appear to be altogether impossible that the ore could be of sedimentary or analogous origin" (75).

The only other accessible report gives a brief but significant description: "The ore of the district consists of a very fine-grained siliceous magnetite,

mixed with a considerable amount of hematite. It is often found interbanded with jasper and green slaty gangue material, which give the deposits a conspicuous bedded structure" (32).

Evidence of igneous influence is more substantial at the Millstream prospect, about 40 km to the northwest: "The ore consists essentially of magnetite in a gangue of garnet, and has a very promiment banded appearance, fairly pure lines, streaks, and thin irregular bands of lenticules of magnetite alternating with similar layers of garnet. Pyroxene, epidote, chalcopyrite, and pyrite also occur in the ore" (75).

These ores are considered tactites. How then, are they to be distinguished from metamorphosed iron-formations of the type described so thoroughly in central Sweden (20)? By what criteria may banding that is the result of metamorphic differentiation be distinguished from banding inherited from a pre-existing iron-formation?

The manganese deposits of northeastern Aroostook County in Maine are definitely not conventional iron-formation, although they are similar in many ways to the manganiferous slaty carbonate iron-formations of the Cayuna Range. They are noted here to illustrate a point discussed in the conclusions.

The deposits of the central district have been developed in an extensive program of drilling, trenching, and mapping. They are said to contain about 10^8 tons of material averaging 11% manganese and 24% iron (17). This "ore" has a pronounced banding, and at first glance looks very much like jasper hematite iron-formation, but the light-red layers are hematite-shale, and the dark red-gray, submetallic layers are composed of braunite and manganese carbonate (52). This rock is rather uniform in composition, but contains, in many places, lenses of carbonate and lenses of chert. It is part of a sequence of lower Paleozoic (Ordovician?) shales apparently several thousand meters thick. The color of these shales—green, gray, red, purple—seems to be closely related to their iron and manganese content and to the ratio of ferric to ferrous iron. The shale in the beds adjacent to the banded ore show a rhythmic alteration of two or more colors.

The ores of the southern district consist of alternating laminae of magnetite and chloritic phyllite, with manganese probably being present as a carbonate. The deposits occur in the argillaceous portions of a sequence of quartzites, phyllites, and limestones that has been dated Ordovician and Gothlandian (74).

The wilderness west of the belt of deposits is a typical eugeosynclinal terrain, with graywackes, lithic conglomerates, greenstone, and graphitic slate. Although considered the same age as the ore-bearing sediments, this assemblage seems to be lacking in sedimentary iron and manganese deposits. Apparently the deposits of the central and southern districts originated under different tectonic conditions while a still different type of environment prevailed to the west (47).

CONCLUSIONS

Summary of Evidence for Paleozoic Iron-formations.—Sedimentary iron-ores that fit the conventional definition of banded iron-formation and are

probably Paleozoic are found in large deposits in the Mato Grosso, Nepal, Norway, Manchuria and Dálnii Vostók. All these occurrences have been dated with fossils, although slight reservations have been expressed in some cases.

Paleozoic ores that resemble iron-formation, but do not fit the strictest definition, include certain deposits in Portugal, West Africa, Spain, Morocco, and the Appalachian Mountains. These deposits are discussed below as possible transitional types.

The Paleozoic banded iron ores of Santo Leone in Sardinia and Bathurst in New Brunswick are considered iron-formations by some, tactites by others. The deposits of Relún in Chile, Cerro Casca in Peru, and the Fleuve Rouge in Tonkin are said to be typical banded iron-formations and are either Paleozoic or older.[11]

In evaluating these examples, consideration should be given to the difficulty of establishing "proof," because a double standard prevails: Paleozoic iron-formations are expected to contain fossils, those in the Proterozoic and Archeozoic need not; the older iron-formations can be dated by intrusives, the younger ones cannot. Most of all, a long tradition that "all iron-formations are 'Precambrian'" has discouraged field men from reporting lone exceptions. This generalization is an open or tacit assumption in nearly every theory on the origin of these deposits proposed in the last fifty years, even though several exceptions were in the literature. Such a persistent belief should not be discarded without accounting for the observations that it seemed to explain.

Comparison of Older and Younger Iron Deposits.—Most theories on the origin of iron-formation are based on two premises: a) these ores are peculiar to the Archeozoic and Proterozoic; b) these ores have special features—banding, chert, great size, lack of detritus—that distinguish them from iron ores of the younger eras. Special time, special features, therefore special conditions of origin, runs the reasoning.

The first premise has been dealt with: banded iron-formations very probably are *not* confined to the older eras. Furthermore, oolitic ores[12] typical of the younger eras occur in the Proterozoic in the Sinian System of China (4), the Transvaal System of South Africa (73) and as facies of the banded iron-formations in the Huronian of the Lake Superior region (26). Even the modified generalization "most banded iron-formations are 'Precambrian'" does not imply special conditions of origin, because these ores

[11] This category may also include deposits in the Postmasburg district of South Africa, and in the Kadapah of India. The old texts, (vonCotta; deLaunay; Beyschlag; Beck; etc.) mention many examples of "itabirite" that they say are either Paleozoic or older. Some have been cited already: Sutton; South Carolina; Tras-os-Montes; Asturias; others include deposits in the Bukovina region of eastern Europe; the Zonwald of Germany; Somorostro in northern Spain; Lampong in southern Sumatra; and several localities in southern France. Significantly, most of these deposits, like most of those cited in the body of the report, are not located in the shields, but in mountain ranges.

[12] Reference is made to "oolitic ores" in a general sense to include both the Clinton- and Lorraine-type ores of Table 3. The term *minette* is too closely associated with the Lorraine ores to be used in this general sense, (10) and is also objectionable as a scientific term because of its obscene synonymity.

were deposited over such a long span of time that they might be considered the "normal" type compared to the relatively restricted oolitic ores.

The second premise, that banded iron-formations have distinctive features, is still significant, but it seems inappropriate to infer special conditions from them, in view of the growing evidence of a closer relationship between the banded and oolitic ores. In the following comparison, therefore, an effort is made to account for the presence of these features in banded iron-formations by reference to a factor that might also explain their absence in the oolitic ores.

Banding—Conventional iron-formations are not the only kinds of iron ore that show banding: the "blackband ores" associated with coal, and the transitional types noted in Table 2 also show this feature. So do many other kinds of sedimentary rocks and ores: coal, evaporites, some manganese ores, bedded cherts, graywacke, and varved lake beds. All have one thing in common: they are thought to originate under conditions of restricted circulation, as are iron-formations. The question is, therefore, why are the oolitic ores *not* banded?

Chert—Cryptocrystalline silica (chert, jasper, silex) is considered an essential component of conventional iron-formation, although it is rare in the sulphide, non-granular silicate, and slaty carbonate facies of the Lake Superior deposits (26). It is also rare in the Clinton-type ores, although some of them contain it as bands in oolites, or dispersed through the matrix. Even more significantly, the Lorraine-type ores are generally free of chert, but contain much detritus. The greater proportion of clastics in these ores indicates a more agitated environment of deposition, and some geologists (26, 55) have suggested that the silica that would have been precipitated as chert in a quiescent locale was combined instead with the clay and iron components of the sedimentary load to form iron silicates.[13]

Size—The tonnage estimates in the literature are made for economic purposes and afford little scientific information, but they at least convey the relative magnitude of the various ore-types. They show that the banded iron-formations, as a class, contain much larger tonnages than the younger ores. The South American, Indian, and Ukrainian shields are said to have more than 10^{11} tons of iron-formation, and some other shields may have comparable tonnages, but realistic estimates are lacking. Few, if any, of the Paleozoic oolitic ore deposits, considered regionally, have as much as 10^{10} tons, and the Mesozoic and Cenozoic deposits are generally smaller. Differences in the thickness of the ore beds are also significant. Most Proterozoic, (and some Archeozoic) iron-formations are *single* units on the order of 10 to 100 m thick, and some are several hundred m thick, whereas most of the younger deposits are *multiple* ore beds 1 to 10 m thick, separated by repetitions of clastics and limestone.

Admixed Clastics—Most banded iron-formations are comparatively free of detritus, and the minor amount they contain is present as distinct beds rather than dispersed. Although iron-formations commonly grade into argillaceous sediments through a thin transition zone (50), very few[14]

[13] The chert problem is discussed in more detail elsewhere (50).
[14] The deposits in West Australia are said to be an exception.

grade abruptly into sandstones, as do the Lorraine-type ores, or into clastic limestone, as do the Clinton-type.

The preceding comparison of conventional iron-formations and the Clinton-Lorraine type ores emphasizes that the latter have no banding, little chert, more detritus, an oolitic structure, are thinner, and occur as multiple beds in complex sedimentary sequences. Apparently they were deposited in a more turbulent environment, where differential settling was inhibited, where silica was not differentiated as chert, but was combined with other colloids to form iron-silicates, and where repeated incursions of clastics interrupted the accumulation of ore so that the beds remained thin and lean.

The banded iron-formations typical of the Proterozoic,[15] on the other hand, being thick and relatively free of detritus, seem to have been deposited under more nearly stable conditions. Many of them are associated with mature, well-differentiated sediments arranged in a sequence that runs: coarse clastics, fine clastics, iron-formation, dolomite (50). This is the standard sequence of transgressive overlap, found in every elementary textbook, but comparatively rare in nature. In implies that the component units are contemporaneous, the clastics being deposited near shore while the colloidal and chemical sediments were being precipitated in deeper water. Conditions of sorting are excellent and if the sediments are from a heavily weathered landmass, they can be separated into silica, clay, and iron-components more readily than in any other environment (48).

Thus, if one factor can explain the distinctive features of the banded iron-formations and also account for the absence of these features from the oolitic ores, that factor is probably tectonic. Vulcanism, climate, composition of the atmosphere, composition of the sea, organisms, and other broad factors are doubtless important, but their rôle in individual deposits is hard to assess, especially in those that show features of both the banded and oolitic ores.

Transitional Ore Types.—Perhaps one reason for the undue persistence of the belief that all iron-formations are "pre-Cambrian" is a misconception inherent in that awkward term. Cutting the whole of geological time into two unequal parts implies a revolution of the first magnitude at the dividing line, yet the "pre-Cambrian-post-pre-Cambrian" boundary does not seem to mark such a major tectonic break. It is a mere disconformity or slightly angular unconformity at many places; the Grand Canyon System of the southwestern United States, the upper Kadapah and Vindhyans of peninsular India, the Sinian System of northern China, the Transvaal System of South Africa, the Buem series of west-central Africa, the Torridonian System of northern Scotland, and other Proterozoic units are said to be comparatively unaffected by diastrophism and metamorphism, and are much more similar to the overlying Paleozoic rocks than to the Archeozoic rocks with which they are lumped. Some sequences, such as the Adelaide System of South Australia, the Rhiphaean System of the Urals, the Sparagmitt formation of

[15] Iron-formations in graywacke suites typical of the Archeozoic and in arkosic suites as exemplified by the Mato Grosso deposits are discussed elsewhere (50).

southern Norway, and the Windemere formation of the northern Rocky Mountains are said to show an unbroken transition from Proterozoic to Paleozoic. With sedimentation so nearly continuous, we might expect to find iron ores intermediate in lithology between the banded iron-formations that characterize the upper Proterozoic and the Clinton ores that typify the lower Paleozoic.

Such transitional types have been reviewed in the body of the report and are summarized in Table 2. They show, on a large scale, what may be seen in the border zones of many typical iron-formations: bands of iron minerals alternating with bands of the country rock (6, 48, 50). Bands of iron oxide alternate with one or more of the following: quartz, quartzite, argillaceous rock, dolomite, tuff, manganese minerals. Some of these ores contain jasper, and the quartz or "quartzite" of others may be recrystallized chert, which means that they are related to the banded iron-formations. On

TABLE 2

TRANSITIONAL IRON-ORES

District	Banding	Chert	Quartz	Argil.	Chlor.	Carb.	Oolites	Grade	Age
Moncorvo	x		x	x	x		x	+50%	Ord
Vila Cova	x		x	x	x		x	45–55%	Ord
Kayes	x	x	x	x				45–55%	Ord
Setolazar	x		x	x			x	+50%	Ord
Asturias	x		x	x	x	x		"Rich"	Cam
Talladega	x		x	x				40–60%	Cam
Cartersville	x	?	x	x		x	x	"Rich"	Cam
Catoctin	x		x	x				35%	Cam
App. Pied.	x	?	x	x	x			"Rich"	Pal?
Sutton	x	x	x	x	x	x		?	Ord
Aroostook	x	x		x	x	x		24% Fe-11% Mn	Ord
Phulchoki	x	x	x		x	x	x	56%	Pal
Mato Grosso	x	x				?	x	+50%	Pal

the other hand, several deposits have an oolitic facies, or can be correlated with oolitic ore in nearby districts, which means that they are also related with the Clinton-type ores. Yet nearly all of them are much richer in iron than these other types, which emphasizes that they do not fit into any existing classification of sedimentary iron ores. Finally, all the known examples are either Cambrian or Ordovician, the age appropriate for the expected transitional types.

The close genetic connection between the older and younger ore types has been stated most explicitly by James (26), who recognizes four distinct facies of iron-formation in the Lake Superior region, each with analogues among ores of the younger eras, and concludes that the differences that distinguish them are "differences of degree rather than kind." He also shows how facies changes within a bed of iron-formation and changes in ore lithology within a sedimentary basin reflect changes in tectonic conditions (25, 26). By analogy on a larger scale, changes in the type of sedimentary iron ore

that predominates from one period to the next, like those just outlined, may also reflect changes in tectonic conditions.

Sedimentary Iron Ores and Tectonic Evolution.—Just as banded iron-formation predominates in the older eras, so various other ore types characterize different parts of the younger eras. This can be seen very clearly in a new classification that Blondel (10) has distilled from the mass of data gathered in two recent world symposia on iron ore. The ore types and the ages of which are are typical are given in Table 3.

The same progressive change in ore lithology can be followed in the history of individual geosynclines, for example, the Appalachian: a) banded iron-formation and transitional types in the Cambrian of the Valley-and-Ridge and piedmont provinces; b) Clinton ores in the Ordovician of Newfoundland and the Gothlandian of New York, Alabama and intervening states; c) Black-

TABLE 3[16]

THE BLONDEL CLASSIFICATION OF THE SEDIMENTARY IRON ORES

Lorraine—oolitic; limonite and iron silicates; minor carbonate and hematite; abundant detritus; Mesozoic and Cenozoic

Blackband—siderite and carbonaceous claystone in alternating bands; associated with coal; Carboniferous and Permian

Lahn Dill—massive, non-oolitic hematite; associated with volcanics; Devonian

Clinton—oolitic; hematite with carbonate matrix and minor clastics; Ordovician, Gothlandian

Lake Superior—banded iron-formation; alternating bands of iron minerals and silica; Archeozoic and Proterozoic

(Translated and Modified.) (10)

band ores in the Carboniferous of Pennsylvania; d) Lorraine ores in the Tertiary of the southern states. A complete progression can be drawn from the Hercynian belt of Europe and nearly complete ones from the Andes, Himalayas, and other tectonic zones. Most of the shield regions show only iron-formation, although many have two main varieties, one in a graywacke-greenstone suite of the kind often considered typical of the Archeozoic, and one in a suite of well-differentiated sediments like those commonly found in the Proterozoic. If more information were available on the rocks associated with the other types of iron ore, it might be possible to show that each type is found in a characteristic tectonic suite, the Clinton ores in the miogeosyncline, the Blackband ores in the unstable shelf, and so forth.

At present, it is only possible to suggest that the apparent change of iron-ore lithology with time is probably a reflection of changing tectonic conditions on a world scale. To the extent that sedimentary basins evolved along

[16] Exceptions to the age grouping (Lake Superior types in the Paleozoic, Lorraine types in the Proterozoic, etc.) and the lithologic grouping (such as the transitional types described above) do not detract seriously from this classification, but merely point out that the so-called "absolute age" of any deposit is of secondary importance compared to its relative age in the history of the sedimentary basin. As noted in a paper by Pettijohn (53) lean, siliceous iron-formation and graywacke were deposited in the Archeozoic of the Canadian shield, in the Proterozoic of the Iron River district of Michigan, (25) and in the Jurassic of northern California (66). (The rhythmically bedded cherts of the Franciscan series are said to contain enough iron, locally, to approach ore.)

parallel lines, they will show a similar sequence of ore types, and to the extent that their development is synchronous, the various ore types will be the same age.

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EXPERIMENTAL INVESTIGATION OF SOLID DIFFUSION AND VOLATILIZATION OF CERTAIN METALLIC SULFIDES

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ABSTRACT

The results of 96 experiments to investigate the behavior of "non-volatile" sulfides below their melting points and in the absence of free oxygen are reported.

Cylindrical pellets of copper sulfide heated in contact with similar pellets of iron sulfide, in nitrogen, reacted at temperatures above 300° C to form layers of bornite and chalcopyrite, mainly in the FeS pellets. The thickness of the layers of reaction products increased with time and temperature. Rock discs placed between two such pellets were veined by chalcocite. Pyrite grains were replaced by chalcocite, bornite, and chalcopyrite.

Copper sulfide heated with iron-rich chlorite showed some reaction at 550° C, but biotite, epidote, bronzite, augite, siderite and calcite showed none.

CuS heated at 300° C and at higher temperatures, recrystallized to chalcocite and digenite. If placed in a temperature gradient above this temperature, it also moved toward the lower temperature at a very appreciable rate. If excess sulfur was removed, no appreciable migration occurred. Iron sulfide and a mixture of CuS and PbS also showed appreciable movement in similar circumstances.

Volatile transfer of iron and copper from sulfides was recorded at 550° C for iron and 675° C for copper.

THE idea of transfer of metals in hydrothermal solutions from an igneous source to the place of deposition, has dominated the thinking of geologists, especially in North America, for the last fifty years. Recently, however, there has been an increasing group of workers who have, by direct statement or implication, supported the view that transfer and concentration of metals may be effected at elevated temperatures in the solid state without the aid of water. So far, these ideas have been based mainly on theoretical considerations and new data in the field of thermodynamics, but the reliable data available so far are, as yet, insufficient to deal adequately with most systems encountered in ore deposits. Indeed, there are many basic facts about simple sulfides and sulfide systems that are still to be determined.

It was with the idea of finding out a little more about the behavior of copper and iron sulfides in the solid state that the experimental work to be described was undertaken. A considerable body of information has been recorded about phase relations in the copper-iron-sulfur system, mainly by workers at the Geophysical Laboratory, Carnegie Institution of Washington (1, 2, 3, 7 and 11 to 18), but little about the intimate details of the movements

of metals through sulfides or of metals or sulfides through rocks in the dry state.

It was therefore decided to explore in this field. While most of the work was done on copper and iron sulfides, a few of the later experiments dealt with others of the "non-volatile" group.

Some of the experiments were suggested in part by earlier work reported by G. M. Schwartz (20), J. E. Hawley (10) and Virginia Ross (19) and by the writings of J. S. Brown (6).

Some of the results obtained should be of interest to students of ore deposits and it is mainly to call attention to these, that this paper is presented. Brief descriptions of all experiments performed are included for the benefit of those who may wish to explore further in this field.

MACDOUGALL'S EXPERIMENTS

The first group of experiments was performed by J. F. Macdougall. Virginia Ross in 1954, studied the reactions between certain sulfide pairs held in contact at temperatures of 130° C and 200° C for periods of from 24 to 96 hours. Cu_2S and FeS did not react at these temperatures. Macdougall decided to investigate this system at higher temperatures. CuS was used instead of Cu_2S because it was readily available in a pure form and yields Cu_2S (or Cu_9S_5) at temperatures below the range used in these experiments.

Preparation of Initial Materials

Cupric sulfide reagent (CuS), precipitated and purified, and granular ferrous sulfide (FeS) were obtained from the Fisher Scientific Company, Montreal. Magnetite, used in a later experiment, was obtained from the geological collection of McGill University. All reagents and minerals used in the experiments were mounted in bakelite and examined with the reflecting ore microscope for impurities. In addition, the ferrous sulfide was X-rayed, the results indicating that it was composed of a mixture of pyrrhotite and troilite. The ferrous sulfide reagent and the magnetite, were found to contain approximately one percent unidentified impurities. The cupric sulfide reagent was free of impurities.

The ferrous sulfide and magnetite were ground to $-150 + 240$ mesh. The cupric sulfide reagent as obtained from the supplier was mainly -240 mesh.

Five to twenty grams of the powders were compressed and heated in a steel cylinder for two hours at 200° C under a confining pressure of 10,000 pounds per square inch, making briquettes or pellets 25 mm in diameter and 7 to 22 mm thick. Cupric sulfide gave the best results, forming a hard, compact material that polished well and resembled fine-grained natural covellite. Ferrous sulfide and magnetite were found to produce a less compact pellet consisting of an aggregate of loosely bonded grains.

Discs cut from natural silicate rocks were used in a few experiments. The pellets were ground and filed to approximately 18 mm in diameter. The

CuS and the rock discs were compact enough to be ground on a steel lap; the FeS and magnetite pellets had to be filed.

Before heating, the compressed pellets were wired together with nichrome wire. A typical specimen ready for heating is shown in Figure 1.

Description of Apparatus

The specimens were placed in a McDanel high temperature combustion tube 24 inches long and approximately one inch inside diameter, lined with Vycor glass tubing. The combustion tube was heated by means of a horizontal Hoskins Heavy Duty combustion furnace. Temperature was controlled by a Fisher Pyrometer Controller using a calibrated chromel-alumel thermocouple. The thermocouple was coated with porcelain cement to prevent contamination by sulfur vapor, and cemented into the combustion

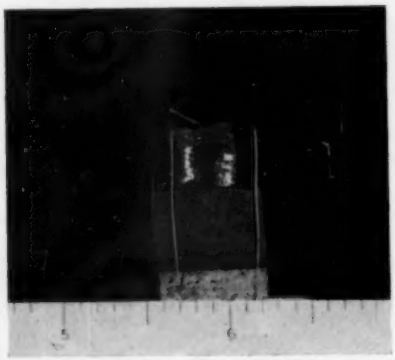

FIG. 1. Typical specimen before heating. Scale in inches.

tube. In all the experiments, the tip of the thermocouple was within one inch of the sample.

One end of the combustion tube was sealed with a Fisher "Breech Connector" cemented to the tube with porcelain cement, or with plaster of Paris coated with water glass. Rubber tubing with a shut-off valve was attached to the other (reduced) end of the combustion tube.

A diagram of apparatus used in later experiments by J. V. Guy-Bray is shown in Figure 2a. This employed a rubber stopper coated with Cello Grease instead of the "Breech Connector" and it had no thermocouple or controller. Temperatures in various parts of the tube were determined by calibration before the experiments were started. Thorough testing showed that fluctuations at any rheostat setting after attaining the calibration temperature were never more than 20° C (Fig. 2b).

After the samples were placed in the tube, the tube was sealed and the air was replaced with nitrogen. In some cases, the combustion tube was

first evacuated before filling with nitrogen. The nitrogen was used in order to maintain a non-oxidizing atmosphere in the tube.

The samples were pre-heated at 125° C for one hour in the combustion tube in order to drive off any moisture present. During this period, a slow stream of nitrogen was passed through the tube.

Following this, the temperature was raised rapidly, (15 to 20 minutes) to the desired holding temperature. This temperature was maintained by

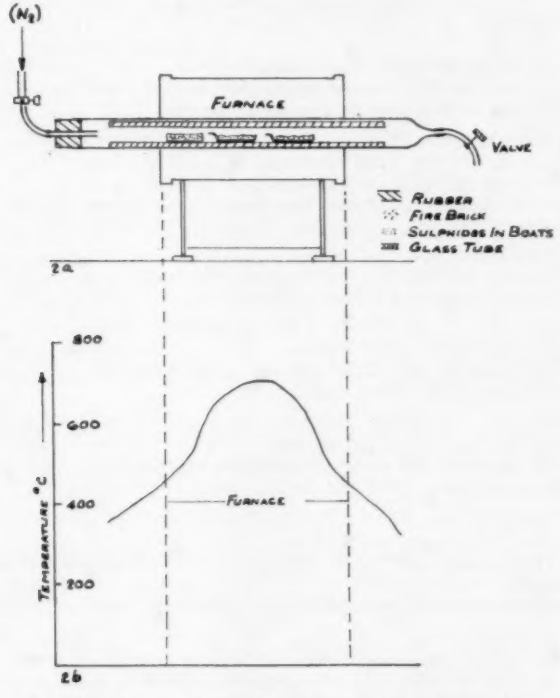

FIG. 2a. Guy-Bray's experimental apparatus (diagrammatic).
FIG. 2b. Temperature distribution in apparatus for a maximum temperature of 700° C.

means of the controller to within ± 10° of the required temperature in Macdougall's experiments.

Method of Analysis of Product

After heat treatment, the specimens were allowed to cool fairly rapidly. The cooling time varied from one and a half to two and a half hours, depending upon the initial temperature.

The specimens were first examined with a binocular microscope and any surface changes noted. One side of the specimen was then ground to a flat surface and polished for examination with a reflecting ore microscope. The more porous and less compact specimens were either impregnated with Canada balsam or mounted in bakelite before polishing.

The minerals were determined using standard procedures, including X-ray diffraction checks in some instances.

Summary of Experiments

Experiment D.S.–2
Initial material—FeS 10 mm, CuS 5 mm.
Conditions—3 hours at 350° C in nitrogen plus evolved sulfur.
Results—Thin film of chalcopyrite formed at contact.

Experiment D.S.–3
Initial material—FeS 9 mm, CuS 13 mm.
Conditions—3 hours at 450° C in nitrogen plus evolved S.
Results—Total thickness of 0.25 mm bornite and chalcopyrite formed.

Experiment D.S.–4
Initial material—FeS 9 mm, CuS 8 mm.
Conditions—5 hours at 450° C in nitrogen plus evolved S.
Results—0.25 mm bornite and 0.5 mm chalcopyrite.

Experiment D.S.–5
Initial material—FeS 7 mm, CuS 6 mm.
Conditions—16 hours at 450° C in nitrogen plus evolved S.
Results—1 mm bornite and 3 mm chalcopyrite.

Experiment D.S.–7
Initial material—FeS 22 mm, CuS 16 mm.
Conditions—16 hours at 450° C in nitrogen plus evolved S.
Results—0.25 mm bornite and 2 mm chalcopyrite.

Experiment D.S.–8
Initial material—FeS 16 mm, CuS 13 mm.
Conditions—16 hours at 450° C in nitrogen. S swept out of combustion tube with nitrogen.
Results—1 mm bornite and 2 mm chalcopyrite formed.

Experiment D.S.–9A
Initial material—FeS 9 mm, CuS 6 mm.
Conditions—24 hours at 450° C in nitrogen plus evolved S.
Results—1 mm bornite and 2.5 mm chalcopyrite.

Experiment D.S.–9B
Initial material—FeS 9 mm and CuS 14 mm.
Conditions—24 hours at 450° C in nitrogen plus evolved S. Specimen moistened with H_2O before heating.
Results—1 mm bornite and 2.50 mm chalcopyrite. Some magnetite present in chalcopyrite.

Experiment D.S.–10
Initial material—FeS 12 mm, CuS 10 mm.
Conditions—24 hours at 550° C in nitrogen plus evolved S.
Results—1.25 mm bornite and 3.75 mm chalcopyrite

Experiment D.S.–11
Initial material—FeS 10 mm, CuS 9 mm.

Conditions—24 hours at 350° C in nitrogen plus evolved S.
Results—0.25 mm bornite with a trace of chalcopyrite.

Experiment D.S.–12
Initial material—FeS 15 mm, CuS 9 mm.
Conditions—24 hours at 650° C in nitrogen plus evolved S.
Results—3 mm bornite and 5 mm chalcopyrite formed in FeS portion. 3 mm mixture bornite and chalcocite formed in Cu_2S portion.

Experiment D.S.–13
Initial material—CuS 12 mm natural magnetite 18 mm.
Conditions—24 hours at 450° C in nitrogen plus evolved S. 5 grams powdered S placed in tube before heating.
Results—2 mm bornite and 2 mm chalcopyrite containing remnants of magnetite. Magnetite in part converted to pyrite.

Experiment W.S.–14
Initial material—FeS 15 mm, CuS 15 mm. In addition two separate pellets of FeS and CuS, 7 mm and 8 mm thick respectively, placed near main specimen.
Conditions—16 hours at 450° C in nitrogen plus evolved S. Several cc's of distilled water added to combustion tube before heating.
Results—1 mm of bornite and 1.5 mm of chalcopyrite. Separate pellets unaltered.

Experiment D.S.–15
Initial material—FeS 15 mm, CuS 11 mm.
Conditions—8 hours in N plus evolved S at 450° C.
Results—0.10 mm bornite and 0.75 mm chalcopyrite.

Experiment D.S.–18
Initial material—FeS 10 mm, "upper" gabbro 5.5 mm, CuS 14 mm, "lower" gabbro 3 mm.
Conditions—24 hours at 450° C in nitrogen plus evolved S.
Results—Chalcocite, bornite and chalcopyrite fill fractures in gabbro. Original magnetite replaced by pyrite, chalcocite, bornite and chalcopyrite.

Experiment D.S.–19
Initial material—FeS 13 mm, "upper" gabbro 5.5 mm, CuS 14 mm, "lower" gabbro 4 mm.
Conditions—24 hours at 450° C in nitrogen plus evolved S.
Results—Chalcocite, bornite and chalcopyrite fill fractures in gabbro. Original magnetite replaced by pyrite, chalcocite, bornite and chalcopyrite.

Experiment D.S.–20
Initial material—FeS 12 mm, Cu_2S 13 mm. FeS was recrystallized by heating at 450° C for 8 hours in S vapor before using.
Conditions—48 hours at 400° C in N. No S vapor present.
Results—1.5 mm bornite and 2 mm chalcopyrite.

Experiment C.D.–1
Initial material—FeS 15 mm, "upper" chlorite 3 mm, CuS 17.5 mm, "lower" chlorite 4 mm.
Conditions—24 hours at 550° C in nitrogen plus evolved S.
Results—Chalcocite, bornite and chalcopyrite fill fractures and partially replaced chlorite. Pyrite replaced by chalcocite, bornite and chalcopyrite.

Experiment C.D.–2
Initial material—FeS 9.5 mm, chloritic rock disc 4 mm, CuS 12.5 mm, "lower" chlorite 3 mm.
Conditions—24 hours at 450° C in nitrogen plus evolved S.
Results—Chalcocite, bornite and chalcopyrite fill fractures and replace original pyrite in rock discs.

Experiments Using CuS and FeS Pellets

Twelve of the experiments listed were carried out to study solid state reactions occurring when CuS and FeS pellets, prepared as described, are heated in contact with one another, and in addition, to study the volatility of these sulfides in sulfur vapor. The specimens were heated in nitrogen at temperatures from 350° C to 650° C for periods ranging from three hours to twenty-four hours.

In all the experiments, two distinct intermediate sulfide phases were formed, bornite and chalcopyrite. The total thickness of the intermediate phases, together, was found to be a function of both temperature and time, following approximately Tammann's Parabolic Rate Rule and agreeing with results obtained by Virginia Ross (19) in experiments on other sulfide pairs.

The FeS had recrystallized and was more compact than the original material. It had absorbed sulfur and was converted wholly or in part to pyrrhotite. Examination of the specimens after heating showed that the CuS decomposed at the temperatures used, yielding chalcocite and/or digenite and sulfur. The sulfides had a cracked and swelled appearance after heating at temperatures of 450° C for periods up to 8 hours. After longer runs, they were less compact. This was evidently due to diffusion of copper out of the Cu_2S into the FeS and loss of sulfur to the atmosphere in the combustion tube. X-ray diffraction determinations showed the presence of both chalcocite and digenite. Samples that had been heated at 650° C for 24 hours had a higher proportion of digenite formed than those heated at 450° C.

The greater thickness of intermediate sulfide phases formed in the FeS portion of the specimen as compared with the Cu_2S portion. After 16 hours at 450° C it was found that copper diffused approximately 2.5 mm into FeS whereas Fe only diffused approximately 1 mm into Cu_2S. At 650° C for 24 hours copper diffused 7 mm into FeS and iron only 3 mm into Cu_2S. The figures for the lower temperatures are lower but similarly related.

Immediately adjacent to the copper sulfide, the original FeS was transformed into bornite; the thickness formed being dependent upon the temperature and duration of heating. The bornite was in turn followed by a layer of chalcopyrite and the chalcopyrite by unchanged FeS or pyrrhotite (Fig. 3).

Although most of the bornite and chalcopyrite were formed in the original FeS portion, some bornite was also formed in the Cu_2S section. The bornite formed by the transformation of FeS was massive and compact while that formed by the transformation of Cu_2S was finely crystalline and mixed with fine grained chalcocite. Many of these bornite crystals were found to be growing one upon another forming wire-like or needle-like crystals. They are up to 1.5 mm long and formed parallel to the long axis of the specimen.

The contact between bornite and chalcocite appears at first glance to be quite sharp. However, examination with the reflecting microscope at high magnifications shows that this is not the case. Adjacent to the contact, the chalcocite contains small angular masses of bornite. Small irregular veinlets of bornite also invade the chalcocite for short distances. Some of the bornite

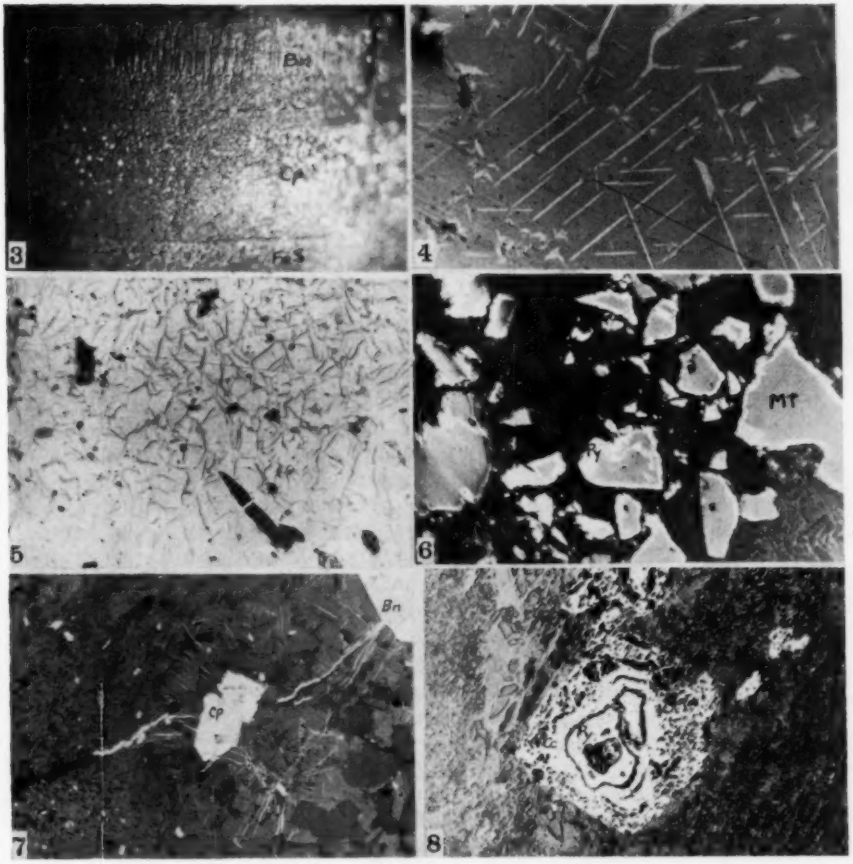

FIG. 3. Development of bornite (Bn) and chalcopyrite (Cp) in FeS. Chalcopyrite is coated with small twinned crystals of bornite. Experiment D.S.–12, 650°—24 hrs. Cp layer 5 mm thick.

FIG. 4. Bornite containing exsolved chalcopyrite. Experiment D.S.–10, 550°—24 hrs. × 160.

FIG. 5. Chalcopyrite containing exsolved bornite. Experiment D.S.–12, 650°—24 hrs. × 160.

FIG. 6. Magnetite (Mt) partly replaced by pyrite (Py). Experiment D.S.–13, 450°—24 hrs. × 160.

FIG. 7. Bornite (Bn) and chalcopyrite (Cp) pseudomorphous after pyrite. Small veinlets of bornite and chalcocite fill fractures near replaced grains. Experiment C.D.–1, 550°—24 hrs. × 75.

FIG. 8. Chalcocite (Cc) pseudomorphous after pyrite (Py). Experiment C.D.–2, 450°—24 hrs. × 25.

masses in the chalcocite contain very fine exsolved blades of chalcocite indicating the formation of a solid solution between the two minerals.

The contacts between the bornite and chalcopyrite and between these minerals and the original sulfides appear to be quite sharp upon first examination, with no extensive zones of intermediate solid solutions. However, detailed examination of polished sections shows that, especially in the higher temperature ranges, a phase intermediate between bornite and chalcopyrite is probably formed at the contact between the bornite and chalcopyrite. This phase is evidently not stable at room temperature and with cooling segregates into bornite containing exsolved laths and blebs of chalcopyrite, and chalcopyrite containing exsolved bornite. With slow cooling, the exsolved material segregates to the grain boundaries forming irregular veinlets or rounded grains. Schwartz (19) reports that bornite and chalcopyrite form solid solutions at temperatures above 475° C. The presence of small areas of exsolved chalcopyrite in bornite noted in an experiment carried out at 400° C for 48 hours indicates that bornite and chalcopyrite can at least form limited solid solutions at this lower temperature. At 450° C the exsolution texture was better developed although still not extensive. Extensive solid solution between bornite and chalcopyrite took place at temperatures of 550° and 650° C as shown by well developed exsolution textures (Figs. 4, 5).

The chalcopyrite layer gradually becomes lighter in color as the pyrrhotite is approached. The exact nature of the paler part of the "chalcopyrite" layer has not, as yet, been determined. The material has a sharp boundary with the pyrrhotite. Remnants of pyrrhotite appear within the "chalcopyrite" in places.

In two experiments (D.S.–8 and 20) S was eliminated from the tube as far as possible; in the first by sweeping it out in a stream of nitrogen and in the second by starting with chalcocite (plus some digenite), produced by heating CuS in nitrogen for 8 hours at 450° C, and pyrrhotite, produced by heating FeS in sulfur vapor at 450° for 8 hours. The results obtained did not differ enough from those of the other experiments to indicate a strong influence of excess sulfur on the rate of diffusion of copper and iron or in the quantity or make-up of the resulting products. The conditions of the experiment were not closely enough controlled to enable one to detect small effects.

In two experiments (D.S.–9A and W.S.–14) water was added to the other materials in the tube. The only effect noted that appeared to have been produced by this change was the formation of magnetite.

In experiment W.S.–14, the CuS and FeS pellets were soaked with water and in addition, several cubic centimeters of it were placed in the combustion tube.

After sealing and evacuating the combustion tube, nitrogen was added and the tube was gradually heated to 450° C. As the water vaporized and the steam pressure built up, small leaks developed, especially near the thermocouple inlet. These leaks were promptly sealed and the release valve opened to relieve the pressure. This was done periodically until the pressure dimin-

ished. The atmosphere inside of the combustion tube for the period of heating (16 hours) may be considered to have been nitrogen plus steam and sulfur vapor. A considerable amount of the evolved sulfur vapor probably escaped with the steam during the intervals when the release valve was open.

Examination of the specimen after cooling showed the thickness of the intermediate phases formed to be slightly less than usual. The average thickness of the bornite and chalcopyrite formed during three experiments at 450° C after 16 hours was approximately 3.0 mm. In this experiment the thickness formed was 2.5 mm. The difference in thickness, however, could be caused by a variety of conditions including the nature of the contact between the original materials as well as the composition and degree of compaction of these materials.

The textures formed were similar to those of experiments performed in a dry atmosphere. The bornite contained blebs and irregular stringers of chalcopyrite representing exsolved chalcopyrite that had migrated to grain boundaries due to slow cooling. Immediately below the contact with the bornite, the chalcopyrite contained a narrow zone composed of chalcopyrite with minute oriental laths of exsolved bornite. The main body of chalcopyrite contained a fine network of magnetite outlining the shapes of the original FeS grains.

Two separate specimens, one composed of CuS and one of FeS were also placed in the combustion tube with the main CuS–FeS specimen. They were separated from one another and from the main specimen by about one inch of fibre glass wool. The object of this was to try to determine if any copper or iron was transferred by the steam. The results indicate that there was no transfer of these materials by the steam. The CuS was converted to chalcocite and the FeS was in part converted to pyrrhotite.

In some of the experiments where the initial materials were heated at 450° C for 16 to 24 hours, small crystals of chalcocite developed on the surface of the Cu_2S, and in some cases the nichrome wires holding the specimen together were also coated with fine twinned crystals of chalcocite up to 0.1 mm in size.

In an experiment carried out at 550° C for 24 hours in nitrogen plus the evolved sulfur vapor, numerous small complexly-twinned crystals of chalcocite formed more abundantly on the surface of the chalcocite pellet, especially near the contact between the Cu_2S and bornite. In addition, small twinned crystals of bornite, averaging 0.01 mm in size, were formed on the surface at the contact between massive bornite and Cu_2S.

At 650° C the formation of bornite crystals was found to be even more conspicuous. Small twinned bornite crystals completely covered the outer surface of the chalcopyrite as well as part of the bornite. The thickness of the layer of crystals was approximately 0.1 mm. On the upper surface of the bornite layer, needle-like crystals of bornite up to 1.5 mm long were formed projecting into the chalcocite.

A ring of iron oxides on the inside surface of the tube near the cool end showed that some iron had been transferred in volatile form at 650° C.

Experiments Using CuS and Fe_3O_4 Pellets

Experiment D.S.–13 was undertaken to study the reaction between Cu_2S and magnetite. The magnetite was crushed to approximately 100 mesh and cleaned by magnetic separation. It was difficult to obtain a clean concentrate, and examination of some of the grains mounted in bakelite revealed the presence of about 5 percent gangue material. The crushed magnetite was then compressed into a pellet 18 mm thick and 18 mm in diameter. This pellet was wired into contact with a pellet of compressed CuS, 12 mm thick, and heated in the usual manner at 450° C for a period of 24 hours. Before sealing the combustion tube and replacing the air with nitrogen, 5 grams of powdered sulfur was placed near one end of the tube. After cooling, most of the excess sulfur was found recondensed near the outlet end of the combustion tube.

Examination of the specimen after heat treatment revealed that the magnetite had been partly transformed into bornite, chalcopyrite and pyrite. A 1 mm thick layer consisting of a mixture of crystalline bornite and "sooty" chalcocite had formed at the base of the Cu_2S. The diffusion of Cu into magnetite was much more active than the diffusion of Fe into Cu_2S, as witnessed by the greater thickness of sulfide formed in the magnetite compared to the Cu_2S. The thickness of bornite was found to be approximately 1.5 mm and that of the chalcopyrite 1.5 mm. The total thickness formed is equal to the amount formed in the system Cu_2S–FeS, indicating that the rate of diffusion of copper into magnetite is about the same as the rate of diffusion into FeS.

Both the bornite and chalcopyrite contain unchanged remnants of magnetite. Near the Cu_2S contact, the magnetite occurs as scattered, rounded residuals surrounded by bornite. The number and angularity of the residuals increases towards the contact between chalcopyrite and magnetite. The chalcopyrite surrounds and also forms irregular replacement-type veinlets in the magnetite. Following the chalcopyrite is a narrow zone showing magnetite rimmed with pyrite, which is in turn partly transformed to chalcopyrite. This zone is followed by original magnetite in part converted to pyrite.

The relationship between the various sulfides was determined by an examination of representative portions of the specimens mounted in bakelite. This was made necessary due to the non-compact nature of the specimen. The exact contacts between the sulfide phases could not be studied by this method. Their nature has therefore been inferred from an examination of the specimen with the binocular microscope combined with a study of the polished bakelite sections. The formation of pyrite takes place from the outer rim of the magnetite towards the centre along an uneven front. In addition, the sulfur has apparently entered along microscopic and semi-microscopic fractures and cleavage planes, forming irregular veinlets and segregated masses of pyrite within the magnetite. Some of the smaller grains of magnetite have been completely transformed to pyrite. This is particularly noticeable close to the outer surfaces of the specimen where the magnetite was in direct contact with the sulfur vapor (Fig. 6).

Experiments Using Rock Specimens

Four experiments were undertaken to study the transfer of sulfides in the "dry" state through rock specimens. A chlorite-rich rock was chosen for the first two experiments, gabbro and meta-gabbro for the third and fourth respectively.

The chlorite-rich rock occurs next to a chalcopyrite-rich orebody at the East Sullivan Mine, Quebec. The material used was collected by R. J. Assad. Examination of a thin section of this rock shows it to be composed of approximately 75 percent fine grained chlorite, 15 percent sericite and 10 percent quartz. Accessory minerals consist of ilmenite and pyrite. The ilmenite occurs as minute laths and blebs in the chlorite and the pyrite as scattered euhedral to subhedral grains, ranging from 0.25 mm to 1 mm in size. Refractive index measurements of the chlorite show that it is of the iron-rich variety and approaches aphrosiderite in composition.

The chlorite-rich rock specimen, hereafter referred to simply as chlorite, was cut with a diamond saw into sections three or four millimeters thick. These sections were then ground to form circular discs approximately 18 mm in diameter. The surfaces of the discs were polished, examined with a reflecting ore microscope, and the minerals noted. One disc was placed between the pellets of compressed FeS and CuS and one at the opposite end of the CuS. The materials were held together with nichrome wire. For the sake of convenience in describing the specimen, the chlorite between the CuS and the FeS will be referred to as the "upper" chlorite, and the one at the opposite end of the CuS as the "lower" chlorite.

In the first experiment, run at 450° C for 24 hours, a disc of chlorite 3 mm thick was placed between pellets of FeS and CuS 15 mm and 17 mm in thickness respectively. In addition, a disc of chlorite 4 mm in thickness was added at the opposite end of the CuS. The second experiment was run at 550° C for 24 hours, using a pellet of FeS 9.5 mm in thickness, and one of CuS 12.5 mm thick. The chlorite disc between the FeS and CuS was 4 mm thick, and the "lower" chlorite 3 mm thick. In both experiments, the specimens were heated in nitrogen plus the sulfur vapor evolved during the dissociation of the initial CuS.

Examination of the specimen that had been heated at 450° showed the FeS to be relatively unchanged except for a slightly lighter color caused by absorption of sulfur, combined with incipient recrystallization. The original CuS was converted to "sooty" chalcocite plus minor digenite. Recrystallization of the copper-sulfide took place adjacent to the contacts with the chlorite, forming a zone of massive chalcocite approximately 1.5 mm thick at either end of the pellet. Small crystals of chalcocite occur on the surface, with concentrations near the contacts with the chlorite.

The "lower" chlorite, immediately below the Cu_2S, shows chalcocite filling fractures in the chlorite and, in a few places, apparently partially replacing it. These chalcocite veinlets vary in width from less than 0.01 mm up to 0.05 mm, and cut across the surface of the specimen. In addition, numerous small "gash" veinlets of chalcocite were noted filling minute fractures along cleavage planes and crystal boundaries of the chlorite and sericite (Fig. 7).

A section through the chlorite normal to the contact shows that the chalcocite penetrated the specimen along fractures to a depth of from 1 to 1.5 mm. Fine crystals of chalcocite and bornite coat the outer surface of the chlorite specimen.

The pyrite grains originally present in the chlorite have in part been transformed into chalcocite, bornite, and chalcopyrite. Immediately below the contact with the Cu_2S the pyrite has been almost completely replaced by chalcocite, and in places chalcocite forms pseudomorphs after pyrite (Fig. 8). This conversion of pyrite into chalcocite necessitates the removal of iron. Apparently the expelled iron combined with the free sulfur present and Cu_2S to form small veinlets and masses of chalcopyrite and/or bornite.

Farther away from the Cu_2S contact, the pyrite grains are replaced by bornite and chalcopyrite. Bornite occurs with only minor amounts of chalcopyrite nearest to the Cu_2S while farther away chalcopyrite predominates (Fig. 7). Approximately 1.5 mm below the contact the chalcopyrite gives way to unchanged pyrite. At this point, a pyrite grain was noted partially rimmed by chalcopyrite.

The "upper" chlorite showed similar transformations.

A second experiment, using chlorite, CuS and FeS as the initial materials with the same arrangement as before, was run at a temperature of 550° C for 24 hours. The results of this experiment were similar, but more striking.

The "upper" chlorite was more extensively fractured than the "lower" chlorite and was completely penetrated by Cu_2S. Penetration into the lower chlorite occurred to a depth of 2 mm. The fractures in both were filled with chalcocite, bornite, and chalcopyrite. They range in width from 0.05 mm up to 0.5 mm. Some have unsupported inclusion of chlorite (Fig. 9). Many of the fractures extend right through the 3 mm thickness of the upper chlorite disc and bornite and chalcopyrite partly replaced the base of the FeS pellet.

The gabbro used in experiment D.S.–19, and meta-gabbro in D.S.–18 were collected by W. James from the Bancroft Area, Ontario. The compositions were as follows:

Gabbro used in experiment D.S.–19:

50%–55%	plagioclase (labradorite)	1–2 mm in size
30%	pyroxene (augite)	up to 1–2 mm
5%	amphibole (hornblende)	less than 1 mm

Meta-gabbro used in experiment D.S.–18:

35%	plagioclase	1–2 mm in size
35%	amphibole (hornblende)	up to 2 mm
10%	scapolite	
10%	magnetite and ilmenite	from 1 to 2.5 mm
Less than 10%	augite	
1%	pyrite	

Both specimens were examined and found to be free from noticeable fractures. The specimens were fashioned into round discs 5.5 mm and 4 mm in thickness and placed in contact with pellets of compressed FeS and CuS, using the same arrangement as in previously described experiments. In

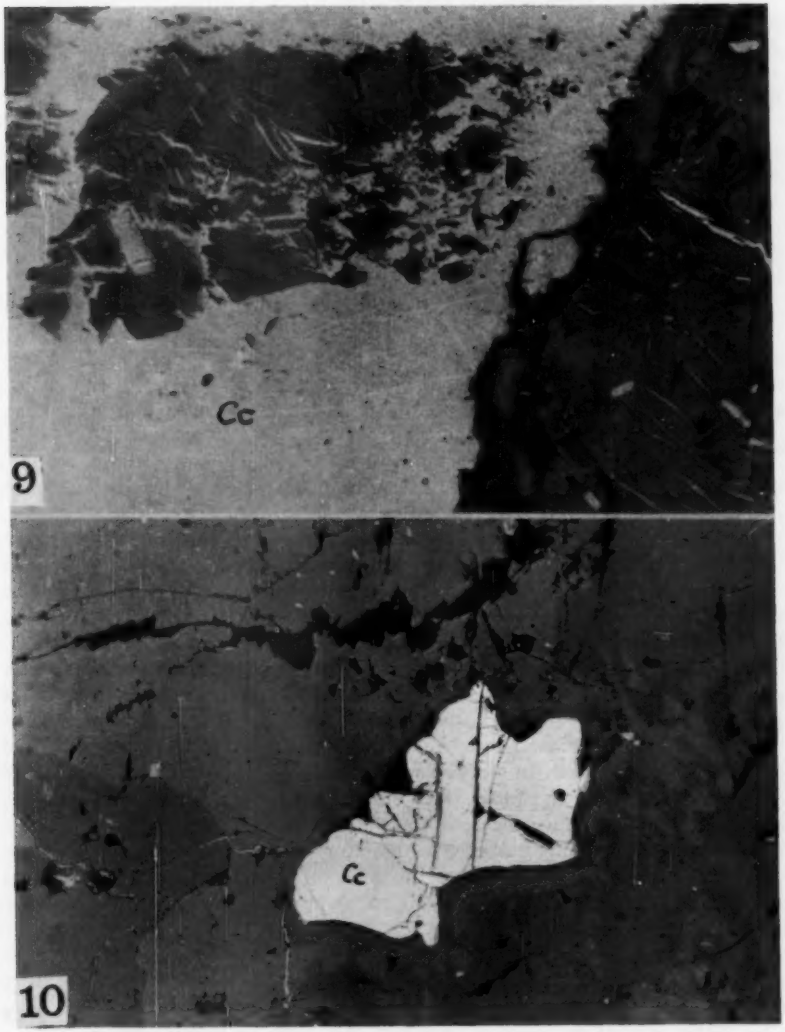

FIG. 9. Inclusions of chlorite in a chalcocite (Cc) veinlet. Experiment C.D.–1, 550°—24 hrs. × 200.

FIG. 10. Chalcocite (Cc) pseudomorphous after magnetite. Ilmenite is unreplaced. Experiment D.S.–19, 450°—24 hrs. × 95.

both experiments using gabbro, the thickest disc was placed between the FeS and CuS. Both FeS-gabbro-CuS specimens were heated in nitrogen plus evolved S for 24 hours at 450° C. Results produced by the heating were similar in both experiments. The following description of results will therefore apply to both experiments.

The FeS pellet in both experiments was found to be partially recrystallized and more compact than initially. The color had changed from dark to light yellowish bronze due to the absorption of sulfur. Small twinned crystals of bornite coat part of the surface of the FeS adjacent to the gabbro. These crystals form a circular area approximately 9 mm in diameter, and were formed by the transfer of Cu_2S either through fractures in the gabbro or around the outer edge of it.

The original CuS was converted to chalcocite and/or digenite and sulfur vapor. Small well-formed crystals of chalcocite were noted coating the surface of the Cu_2S, especially near the contacts with the "upper" and "lower" gabbro. Similar crystals occur as isolated patches on the sides of the gabbro discs. When they formed on top of original pyrite or magnetite grains, chalcocite was in part converted to bornite.

Examination of polished sections of the "upper" and "lower" gabbro reveals that extensive transformations have taken place. The original magnetite grains have been changed either wholly or in part to pyrite, chalcopyrite, bornite and chalcocite, with the chalcocite occurring nearest the contact with Cu_2S. Where magnetite and ilmenite occur intergrown, it was noted that even though the magnetite is completely replaced by chalcocite, the ilmenite remains largely unchanged (Fig. 10). Farther from the contact, the magnetite as well as the few original pyrite grains are replaced by bornite and chalcopyrite, with bornite closest to the Cu_2S. Chalcopyrite rims magnetite and fills fractures in the silicate minerals at a distance of 2 mm from the Cu_2S contact.

Many of the original magnetite grains have been partially converted to pyrite by reaction with sulfur vapor. Pyrite was noted rimming magnetite as well as forming irregular replacement-type veinlets in it. This "pyritization" is most noticeable near the outer surfaces of the specimen where the magnetite was in direct contact with sulfur vapor. However, the presence of partially replaced magnetite in the interior of the gabbro indicates that sulfur has also penetrated the specimen along fractures, and in particular along grain boundaries.

Chalcocite, bornite and chalcopyrite, in addition to replacing magnetite and pyrite, also fill fractures in gabbro. These fractures are widest near the contact with the Cu_2S and diminish in size away from the contact. The size of the veinlets varies from less than 0.01 mm up to 0.02 mm in width, and were noted penetrating the gabbro for a distance of approximately 2 mm from the Cu_2S, with bornite, followed by chalcopyrite, farther away. The iron required to form bornite and chalcopyrite is believed to come mainly from the original magnetite and pyrite grains. When these minerals are replaced by chalcocite, iron is expelled. This iron combines with Cu_2S forming chalcopyrite and bornite. Numerous small discontinuous veinlets of

chalcocite, bornite and chalcopyrite were noted extending outward away from replaced magnetite and pyrite grains.

There is no evidence to show that sulfur vapor reacted with any of the iron-bearing silicates to form iron sulfide, nor has there been any extensive replacement of these minerals by chalcocite, bornite, or chalcopyrite though minor replacement may have occurred locally. All of the veinlets appear to have been formed by fracture filling.

MEIKLE'S EXPERIMENT

B. K. Meikle performed additional experiments using similar equipment. The list of experiments with brief descriptions of results follows. Unless otherwise noted, excess sulfur was placed in the tube along with the materials recorded.

List of Experiments

A–1 to A–5	Magnetite–CuS. 550° C, 24 hrs. Bornite formed at interface and chalcopyrite veinlets in magnetite.
B–1	FeS–Chlorite–PbS, ZnS, CuS mixture. 550° C, 48 hrs. Minor diffusion of chalcocite.
C–1	FeS–Chlorite–CuS, Sb_2S_3, SnO_2 mixture. 550° C, 48 hrs. Stibnite volatilized.
D–1	FeS–2 mm space–CuS. 550° C, 24 hrs. Nil.
E–1	CuS–chlorite, 550° C, 24 hrs. Minor diffusion.
F–1	CuS–limestone, 550° C, 24 hrs. Minor diffusion.
G–1	FeS in CuS. 550° C, 48 hrs. Chalcopyrite nodules formed.
H–1	Gabbro in CuS. 550° C, 48 hrs. Minor diffusion.
I–1	Chlorite in CuS. 550° C, 48 hrs. Minor diffusion.
J–1	FeS–2 mm space–Sb_2S_3. 550° C, 48 hrs. Sb_2S_3 volatilized.
K–1	Gabbro in Sb_2S_3. 550° C, 48 hrs. Sb_2S_3 volatilized.
L–1	Chlorite in Sb_2S_3. 550° C, 48 hrs. Sb_2S_3 volatilized.
M–1	CuS–1½ mm asbestos washer–FeS. 550° C, 48 hrs. Minor bornite between the pellets and on the Cu_2S.
N–1	CuS–1½ mm asbestos washer + sulfur–FeS. 550° C, 48 hrs. Same as M–1.
P–1	$CuFeS_2$, Pyrrhotite veinlet in chloritic rock, 550° C, 8 hrs. Nil.
Q–1	Chlorite in CuS. 550° C, 48 hrs. Diffusion and possibly minor replacement.
R–1	Iron-rich chlorite in CuS. 550° C, 48 hrs. Diffusion and replacement. Minor bornite in Cu_2S.
S–1 to S–2	CuS–Magnetite. 550° C, 24 hrs. Attempt to set up an electrical potential failed. Results as in A–1 to A–5.
U–1	Bronzite in CuS. 550° C, 24 hrs. Minor diffusion.
V–1	PbS, CuS, FeS mixture, 200° C–550° C, 24 hrs. Diffusion.
V–2	PbS, CuS mixture, 200°–550° C, 24 hrs. Diffusion.
W–1	Augite in CuS. 550° C, 48 hrs. Minor diffusion.
X–1	Biotite in CuS. 550° C, 64 hrs. Minor diffusion.
X–2	Biotite in CuS. 550° C, 40 hrs. H_2O present. As in X–1.

Y–1 Augite, epidote and siderite in CuS. 550° C, 48 hrs. H_2O present. Minor diffusion.

Z–1 Chlorite, biotite, epidote and augite in CuS. 825° C, 48 hrs. Minor diffusion and possibly replacement of chlorite.

Z–2 Chlorite, biotite, epidote and augite in CuS. 285° C, 169 days. Nil.

AB–1 CuS–1″ space–Fe. 680° C, 21 hrs. Copper transferred.

AC–1 CuS–Stream of S and N. 550° C, 6 hrs. Appreciable diffusion.

AD–1 FeS_2–3″ space–CuS. 550° C, 24 hrs. Sulfur pressure 0.77 atmos. Fe transferred.

AE–1 CuS–3″ space–Fe. 475° C, 24 hrs. Nil.

AE–2 CuS–3″ space–Fe. 775° C, 17 hrs. Copper transferred.

AF–1 Three chlorites in CuS. 550° C, 48 hrs. Sulfur pressure 0.75 atmos. Two iron-rich chlorites definitely partly replaced.

AG–1 FeS_2–3″ space–CuS. 550° C, 37 hrs. Fe transferred.

AG–2 FeS_2–3″ space–CuS. 550° C, 37 hrs. All vapor evolved in first two hours flushed out. Nil.

AH–1 PbS, CuS mixture, 200°–550° C, 24 hrs. Diffusion.

AH–2 PbS, CuS mixture, 200°–550° C, 24 hrs. All vapor evolved in first two hours flushed out. Minor diffusion.

AJ–1 CuS–space–Fe. 655° C, 24 hrs. No excess S. No Cu transferred.

AK–1 Repeat of AF–1.

AL–1 CuS pellet–3″ space–Fe. 675° C, 24 hrs. Cu transferred.

AM–1 Iron-rich chlorite in CuS. 550° C, 48 hrs. Sulfur pr. 0.75 atmos. Chlorite crystals partly replaced.

In experiments AD–1, AF–1 and AM–1, specimens were heated in vacuum tubes made of Corning 172 glass tubing. The outside diameter of the tubing was 20 mm and the wall was 2½ mm thick. To melt the glass, a mixture of oxygen, natural gas and compressed air was used. One end of the tube was closed and the sample was inserted. The other end of the tube was then drawn out into a thin tube. The gas inside the tube was evacuated and replaced by nitrogen three times, then the final seal was made by melting the thin tube. The pressure inside the tube at room temperature was four mm of mercury.

Discussion of Results

Volume solid diffusion was observed in several of the experiments, and the results were in accord with those found by previous workers.

In experiments A–1 to A–5, chalcocite and magnetite reacted to form the intermediate phases bornite and chalcopyrite. The amount of the intermediate phases formed varied erratically due to the variable nature of the contact between the pellets. The aluminum wire used was too weak to bind the pellets tightly together, and when the wire expanded on heating, the contact must have been very poor. Macdougall used nichrome wire and obtained reproducible results.

In experiment G–1, a better method was devised. A pellet was made by compressing FeS 5 mm on a side in a matrix of CuS. The time of heating was too long as, after heating at 550° C for 48 hours, the entire pellet had been altered to chalcopyrite.

Macdougall has shown that this particular phenomenon of volume solid diffusion proceeds at approximately the same rates whether the system is in a S and N atmosphere or N only. This is in marked contrast to the effect of S on those processes that govern the migration of material away from the main mass of sulfides.

In experiments C–1, J–1, K–1 and L–1, stibnite was present, and at 550° C, the temperature at which the experiments were performed, stibnite is quite volatile. Although the stibnite had partly volatized, no stibnite veinlets were found in cracks in adjacent specimens, and no crystals had formed on the surface of the remaining stibnite. Stibnite had been deposited on the walls of the tube and was especially concentrated near the cold end of the tube.

Chalcocite behaved in a markedly different manner. In the numerous experiments at 550° C in S and N atmosphere, chalcocite crystals formed on the surface of the chalcocite pellets, and chalcocite veinlets penetrated cracks and cleavage planes in adjacent minerals to a depth of as much as 10 mm in 48 hours. No chalcocite was found deposited on the walls of the tube.

The force of gravity appears to have some effect on individual mobile molecules, as in many of the experiments the space between the bottom of the tube and the glass containing-tube was completely filled with crystals. In experiment AC–1, the chalcocite pellet appears to have sagged downwards. This might have been due to the action of gravity on individual diffusing molecules, but more probably was due to a decrease in the strength of the pellet as a whole.

Experiment AC–1 showed that in six hours chalcocite migrated as a porous solid, 0.3″ along the bottom of a glass tube in the direction of flow of a stream of nitrogen and sulfur vapor. The mobile chalcocite also migrated up the side of the tube. Migration against gravity was also noted in experiment AH–1.

Experiments V–1, V–2, AH–1 and AH–2 indicated that a mixture of PbS and Cu_2S will move down a temperature gradient as a unit. No large-scale mineral zoning takes place. X-ray fluorescence studies of six samples taken from different parts of the specimen in experiment AH–1 revealed that the Cu-Pb ratio was identical no matter what the temperature of the sample had been. The pseudo-eutectic unmixing texture that developed (Fig. 11) did not indicate that flowage had occurred but the macro-structure gave good evidence of migration. Where the specimen had been hottest, there was less material and waves of material had built up on the surface. The material that had originally been tightly packed powder was a porous solid after the experiment.

Experiment AG–2 and AJ–1 indicate that in the absence of sulfur vapor there is no evidence that diffusion had occurred at temperatures as high as 655° C. The covellite altered to chalcocite, but no large chalcocite crystals were formed on the surface, and the original rectangular prism retained its shape.

In experiments A–1 to A–5 sulfur vapor and magnetite reacted to form pyrite, magnetite and chalcocite reacted to form bornite and chalcopyrite,

and bornite and magnetite reacted to form chalcopyrite. The replacement may have taken place volume for volume, but there was no good evidence for this as none of the minerals appeared to be pseudomorphic after magnetite.

At atmospheric pressure, at 550° C and in a N and S atmosphere, the following minerals appeared to be unreplaced by chalcocite: calcite, siderite, biotite, epidote, bronzite and augite. Even when they were heated at 825° C for 48 hours, biotite, epidote and augite did not appear to be even slightly replaced by chalcocite.

In several of the early experiments, chlorite with a low iron content was heated with chalcocite and, although the resulting texture suggested that

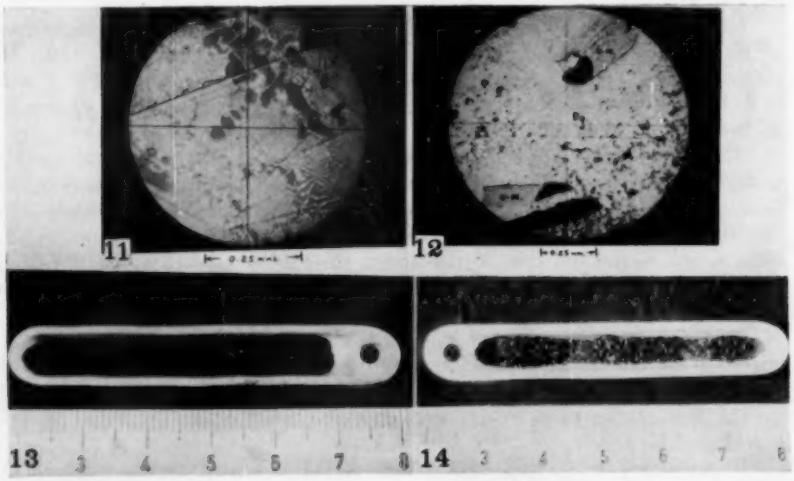

FIG. 11. Pseudoeutectic unmixing texture: chalcocite (gray) and galena (white). Experiment AH–1, 550°—24 hrs.

FIG. 12. Chlorite replaced by unidentified material (U.M.) in matrix of copper sulfide. Experiment AM–1, 550°—48 hrs.

FIG. 13. Sulfide in combustion boat before firing; scale in centimeters.

FIG. 14. Small "flow" of copper sulfide up cooler (left) end of boat. Scale in centimeters.

minor replacement had occurred, there was no definite evidence. The chlorite grains had been penetrated by chalcocite, and many of the veinlet walls did not match each other, but only rarely was a minute speck of an iron-bearing sulfide observed, and no new silicate minerals appeared to have been formed.

In experiment R–1, an iron-rich chlorite was used and replacement of the chlorite crystals by a different type of material took place. Minor bornite occurred in the chalcocite.

Similar results were found in experiments AF–1, AK–1 and AM–1, which were performed under a sulfur pressure of 0.75 atmospheres. In these

experiments no bornite was found in the copper sulfide. There was no definite evidence for the replacement of the iron-poor chlorite, although the texture suggested that some replacement had occurred but in the iron-rich chlorites, the replacement texture had been well developed (Fig. 12).

The nature of the material replacing the chlorite crystals is not definitely known. The material obtained in experiment R–1 was examined with a petrographic microscope and was cloudy and almost opaque. When a polished specimen of the product of experiment AM–1 was examined under a reflecting microscope with an oil immersion lens, the material appeared to be neither a single grain of a sulfide mineral nor a single grain of a silicate mineral. It did have a distinct pink color, but all reactions with the standard chemical reagents were negative.

The altered specimen of experiment AM–1 was crushed, and by heavy liquid separation, a fraction containing approximately 90 percent chlorite and 10 percent of the material replacing the chlorite crystals was obtained. This fraction was compared by X-ray fluorescence and X-ray diffraction to the original chlorite and to a specimen of the original chlorite that had been heated in nitrogen for 48 hours at 550° C. This latter specimen was examined with a binocular microscope and no visible replacement of the chlorite crystals had occurred.

X-ray fluorescence showed that all three specimens contained the same amount of iron. In experiment AM–1, therefore, iron if it migrated from the chlorite into the adjacent copper sulfide was too low in amount to be detected.

Most crystalline materials will cause discernible diffraction peaks if they are present in amounts greater than a few percent. For example, 1 percent quartz in chlorite is readily detected. As no new peaks showed up in the X-ray diffraction curve of the specimen from experiment AM–1, and as the material replacing chlorite formed about 10 percent of the specimen, it is assumed that either this material was poorly crystallized, or that it also was a chlorite.

Brindley (5) showed that heating magnesian chlorites to 600° C drives off four out of six OH groups from the brucite part of the structure. This material still gives chlorite diffraction peaks, but the intensity of the 001 peak (8°) is increased, and the intensities of the 002 and 003 peaks (15.9° and 23.8°) are decreased.

The intensities of these peaks, in counts per second, were respectively, 308, 1130 and 272 for the unaltered chlorite, 860, 375 and 95 for the heated chlorite, and 113, 233 and 60 for the heated and partly replaced chlorite of experiment AM–1.

The differences in the peak intensities of the unaltered chlorite and the heated chlorite may be due to a partial dehydration as described above.

The peak intensities of the heated chlorite are greater than those of the heated and partly replaced chlorite. This does not appear to be due only to dilution of the chlorite by poorly crystallized material, as if this were so, the peak ratios would be identical. If the replacing material is a second well crystallized chlorite, the intensities of the reflections of the two chlorites

combined would have been greater than those observed. Variations in the intensities of the X-ray reflections may be due to variations in the iron content, variations in the degree of dehydration, and slight variations in the mounting technique causing preferred orientations of the chlorite, as well as to variations in the amount of chlorite present.

Since the replacement of chlorite in these experiments was observed only in association with the sulfides, it is a reasonable presumption that their presence had something to do with it, though it is not possible at this time to define the reaction.

Minor amounts of bornite may be present in the material which replaced the chlorite. Less than 0.1 percent would probably not be detected by X-ray diffraction, but might still be enough to cause the pink color noticed under the reflecting microscope.

No change was observed in any of the other silicates or carbonates used in these experiments.

Several experiments were performed to see if iron or copper could be transferred as a vapor in appreciable quantities.

Three experiments were performed at 550° C with pellets of pyrite and what was originally covellite placed 3″ apart. In experiment AD–1, the sulfur vapor pressure was 0.75 atmos.; in experiment AG–1 excess sulfur was present and although the sulfur pressure was not known, it was probably less than 0.75 atmos. In experiment AG–2, there was no sulfur vapor present.

X-ray fluorescence studies revealed that no copper had been transported to the pyrite but that iron had been transported to the chalcocite in experiments AD–1 and AG–1. The results show that in experiment AB–1 after 24 hours the digenite, which weighed 0.350 grams, had absorbed 0.46% Fe, and in experiment AG–1 the chalcocite, which weighed 1.015 grams, had absorbed 0.2% Fe in 37 hours.

In experiments AB–1, AE–1, AE–2, AJ–1 and AL–1, chalcocite and an iron nut were placed 3″ apart. It was found that copper was transported at temperatures above 675° C if excess sulfur was present in the atmosphere. No iron was transported to the copper sulfides.

In experiment AB–1 an air leakage caused the outside layer of the pyrrhotite (which had formed by the reaction of the sulfur vapor with the iron nut) to be altered to magnetite. Chalcocite was deposited on the magnetite, but due to plucking during the polishing process, the actual chalcocite-magnetite contact could not be observed. The chalcocite had a definite pink tinge, which was probably due to a high iron content acquired by reaction with the magnetite.

In experiment AL–1 chalcocite appeared to have been deposited on the pyrrhotite and much of the chalcocite had reacted with the pyrrhotite to form bornite. Fern-like crystals formed on the surface of, and replaced pyrrhotite.

The nature of the gaseous molecules in these experiments is not known. Gaseous transportation could not be effected except in the presence of sulfur vapor, so it seems likely that some type of sulfide molecules were involved.

GUY-BRAY'S EXPERIMENTS

J. V. Guy-Bray experimented with various sulfides, especially those classed as nonvolatile in a vacuum by Hsiao and Schlechten (10).

His efforts were directed toward exploring more fully the effect of sulfur vapor on the volatility of the sulfides. Striking surface diffusion was observed and received considerable attention.

The equipment used was essentially the same as that employed by Macdougall and Meikle and is shown in Figure 2. Specimens were, however, in loose powder form, placed in porcelain combustion boats (Fig. 13) and loaded into the glass tube at selected places. Many were deliberately placed in a steep temperature gradient.

The atmosphere in the tube during all these experiments, except No. G.B. 22, consisted of nitrogen and sulfur vapor. The procedure, basically, was to heat a sulfide near the hottest part of the tube, and attempt to detect its movement towards the cool ends of the tube. Other sulfides, fire-brick, porcelain and wire were used to provide sites for deposition of volatile matter.

In many of the experiments, X-ray fluorescence was used to detect changes in the metal content before and after firing. Attempts were also made to detect transfer of sulfides by changes in weight. However, the sulfides are by no means stoichiometric, and it soon became clear that changes in the sulfur content caused far greater weight changes than did volatilization of sulfides. A charge was frequently heavier after firing; weighing was therefore abandoned.

The experiments are grouped below in terms of the sulfide whose volatility was being investigated. Thus if FeS was used to precipitate volatile ZnS, the experiment is listed under Zinc Sulfide (though information on the volatility of FeS may also have been acquired). Experiments designed to examine the volatility of more than one sulfide are grouped in at the end.

List of Experiments

Expt. No.

G.B. 1. PbS powder. 700° C, 6 hours
PbS recrystallized; considerable visible evidence of volatilization.

G.B. 2. ZnS powder. 700° C, 24 hours
ZnS appeared slightly recrystallized, but there was no visible evidence of transport.

G.B. 3. ZnS powder. 1,000° C, 61 hours
Recrystallized, slight surface diffusion. X-ray fluorescence showed that volatile transfer of Zn had occurred.

G.B. 4. MnS powder. 700° C, 48 hours
No change in the MnS and no transport detected.

G.B. 5. MoS_2 powder. 700° C, 90 hours
No change in the MoS_2 and no transport detected.

G.B. 6. MoS_2 powder. 1,000° C, 24 hours
No change in the MoS_2 and no transport detected.

G.B. 7. MoS_2 powder. 1,000° C, 51 hours
Slight recrystallization of MoS_2 and no transport detected.

G.B. 8. FeS powder. 700° C, 48 hours
Slight recrystallization of FeS and no transport detected.

G.B. 9. FeS powder. 700° C, 67 hours
Slight recrystallization of FeS and no transport detected.

G.B. 10. FeS powder. 700° C, 110 hours
Slight recrystallization of FeS and no transport detected.

G.B. 11. FeS powder. 1,000° C, 48 hours.
FeS completely recrystallized, no visible transport. X-ray fluorescence revealed no transfer of iron to the copper sulfide "detector."

G.B. 12–18 (incl). CuS powder. 700° C, 24 hours
Series of unsuccessful attempts to detect volatility using other sulfides, firebrick, porcelain, and wire. Surface diffusion phenomena and growth of crystals studied.

G.B. 19. CuS powder. 700° C, 69 hours
Considerable surface diffusion, with minor evidence of volatilization.

G.B. 20. CuS powder. 1,000° C, 49 hours
Surface diffusion and minor associated volatile transfer seen. X-ray fluorescence revealed no transfer of copper to the iron sulfide "detector."

G.B. 21. CuS powder. 1,000° C, 48 hours
Considerable surface diffusion, with visible evidence of volatilization.

G.B. 22. CuS powder. 1,000° C, 48 hours
Atmosphere kept free of sulfur vapor by continuous flushing with N. Slight recrystallization and no surface diffusion. X-ray fluorescence detected no transfer of Cu.

G.B. 23. Linnaeite and chalcopyrite powder mixed. 1,000° C, 50 hours
Charge recrystallized with minor volatilization. X-ray fluorescence detected no transfer of cobalt.

G.B. 24. NiS powder. 750° C, 72 hours
No change in the NiS and no transport detected.

G.B. 25. NiS powder. 800° C, 25 hours
NiS partially melted. X-ray fluorescence detected no transfer of Ni.

G.B. 26. Mixture of CuS and FeS packed into Vycor tube to form cylindrical charge. 700° C, 24 hours
No volatile transfer detected. Charge transformed to chalcopyrite.

G.B. 27. Mixture of CuS and FeS in combustion boat. 500° C, 48 hours.
Charge transformed to chalcopyrite but no transport detected.

G.B. 28. Separate charges of CuS, FeS, MoS_2 and MnS. 200–300° C, 255 days
FeS and CuS recrystallized, other sulfides unchanged.

G.B. 29. Separate charges of FeS and MnS. 1,000° C, 24 hours
FeS recrystallized with minor surface diffusion. MnS unchanged. No volatile transfer detected.

G.B. 30. Four separate charges of CuS and FeS. 1,000° C, 48 hours
FeS recrystallized; both sulfides show surface diffusion. X-ray fluorescence revealed little evidence of volatile transfer.

G.B. 31. Separate charges: ZnS and a mixture of Co_3S_4 and $CuFeS_2$. 950° C, 48 hours
Under the influence of a steep thermal gradient, minor surface diffusion occurred in both boats. A little associated volatilization took place in the boat containing the Co_3S_4 and $CuFeS_2$.

Discussion of Results

Lead Sulfide.—The volatility of the PbS under the conditions of experiment G.B. 1 (700° C) was clearly demonstrated by the spectacular transfer

of sulfide to the sides of the combustion boat and the glass tube. Some surface diffusion was also noted.

Zinc Sulfide.—Volatile transfer of zinc from ZnS at 1,000° C to copper sulfide at around 900° C was detected in experiment G.B. 3. No transfer was detected in experiment G.B. 2 at 700° C. Comparison of X-ray fluorescence charts of FeS heated at various temperatures (experiments G.B. 3, 25, 30) showed that zinc present as an impurity was lost at temperatures as low as 600° C.

Manganese Sulfide.—The manganese sulfide was heated at temperatures up to 1,000° C but in no case was any change observed in it, not even the slightest recrystallization, nor was any volatilization detected.

Molybdenum Sulfide.—After 51 hours heating at 1,000° C a slight hardening of the surface of the charge was observed. This was thought to be due to minor recrystallization. Apart from this weak evidence of mobility, the molybdenum sulfide behaved as inertly as the manganese sulfide and no volatilization was detected.

Iron Sulfide.—No visible volatilization of iron sulfide occurred under any conditions and recrystallization was sluggish at 700° C, though it was detected in experiment G.B. 28 at about 250° C. Surface diffusion was quite vigorous at high temperatures. Copper sulfide was used as a detector in experiments 11 and 30, but X-ray fluorescence failed to show any increase of iron in it. However, iron present as an impurity in CuS showed some diminution on heating to 900° ± 50° C in experiments G.B. 11 and G.B. 30, suggesting volatile transfer. At higher sulfur pressures (0.75 atmospheres) Meikle got more definite evidence of transfer of iron as a vapor at temperatures of 550° to 650° C. Iron sulfide used as a detector for copper in experiment 20 showed wasting at the hotter end and heaping up at the cooler end, attributed to surface diffusion (Fig. 14).

Copper Sulfide.—Copper sulfide was conspicuously mobile in most of the experiments. It crystallized readily, even below 300° C and at higher temperatures developed twinned crystals several millimeters in diameter. Its vigorous surface diffusion was an outstanding feature. At 1,000° C and in a longer experiment (G.B. 19) at 700° C there was visible evidence of volatile transfer of copper. Discrete crystals of copper sulfide were found on the sides and ends of the combustion boats. It is possible, though unlikely, that some of the smaller crystals were thrown there by decrepitation. However, there is more convincing evidence. A number of isolated copper sulfide bodies up to 5 mm long were found on the top and sides of pieces of fire-brick placed in the tube, down the temperature gradient from the charge. A few such crystals were first observed in experiment G.B. 19 at 700° C and more were readily produced at 1,000° C in experiment G.B. 21. Volatile transfer seems to be the only possible means of accounting for their deposition on the brick. The most distant crystal in experiment G.B. 21 was 4 cm from the charge in the boat.

In several of the copper sulfide experiments, a brown film formed a diffuse ring on the inside surface of the glass tube at about the 500° C mark. There was never enough material for identification. It seems unlikely that the film

was of sulfur, crystals of which were invariably found much nearer the cool end of the apparatus. It could conceivably be a copper oxide, formed by the reaction of heated volatile copper sulfide with any oxygen remaining in the tube.

X-ray fluorescence charts for FeS heated to 1,000° C in experiments G.B. 20 and 30 showed some decrease in Cu, present as an impurity, indicating some volatile transfer.

Recrystallization evidently demands some sort of diffusion, and as noted above, copper sulfide recrystallized even below 300° C. Higher temperatures and longer heating produced larger crystals.

As long as the charge was placed in the center of the furnace, at the flattened crest of the temperature gradient curve, there was little change beyond recrystallization. However, if the boat was arranged so that a temperature difference existed between its ends, there occurred a migration of sulfide towards the cooler end. The migration proceeded by the progressive growth of connected crystals along a continuously advancing front, and appears to be an excellent example of surface diffusion.

Every stage of the phenomenon was observed, beginning with a slight loss of sulfide at the hot end of the boat and a slight gain at the cooler end, and continuing through a series of stronger manifestations (Figs. 14, 15) that show the diffusion of sulfide up and over the ends of the combustion boats. A photograph of the underside of a sulfide charge (Fig. 16) shows the aligned form assumed by the crystals under the influence of the temperature gradient.

The most spectacular example of surface diffusion occurred in experiment G.B. 19 (700° C—69 hrs.) in which a "flow" of sulfide crossed a 2 mm gap to a piece of fire-brick, and continued to advance across this (Fig. 15).

The magnitude of the transfer of sulfide effected by surface diffusion as described above was found to vary with the temperature gradient, with the temperature, with the duration of heating, with the sulfur vapor pressure (experiment G.B. 22), and with the nature of the surface. This last is indicated by the observation that in several experiments a considerable "heaping-up" of the charge was produced at the cooler end of the boat, evidently by transfer of sulfide from the hotter parts, while the "flow" of sulfide advancing over the porcelain end of the boat was by comparison quite small and thin. It appears that sulfide diffusion is easier over a sulfide surface than over a porcelain one. This is in agreement with data cited by Barrer (4), which show that a much higher activation energy is required for migration if the surface concentration of the migrating atoms is low. Evidently, the concentration of copper sulfide on the porcelain surface is vanishingly small.

Surface diffusion in the other sulfides was much less conspicuous. To promote volatilization, the sulfides examined were usually placed at the hottest part of the tube, and the low temperature gradient there was not conducive to rapid diffusion. But even when placed on a steep thermal slope, the behavior of the other sulfides never approached that of copper sulfide.

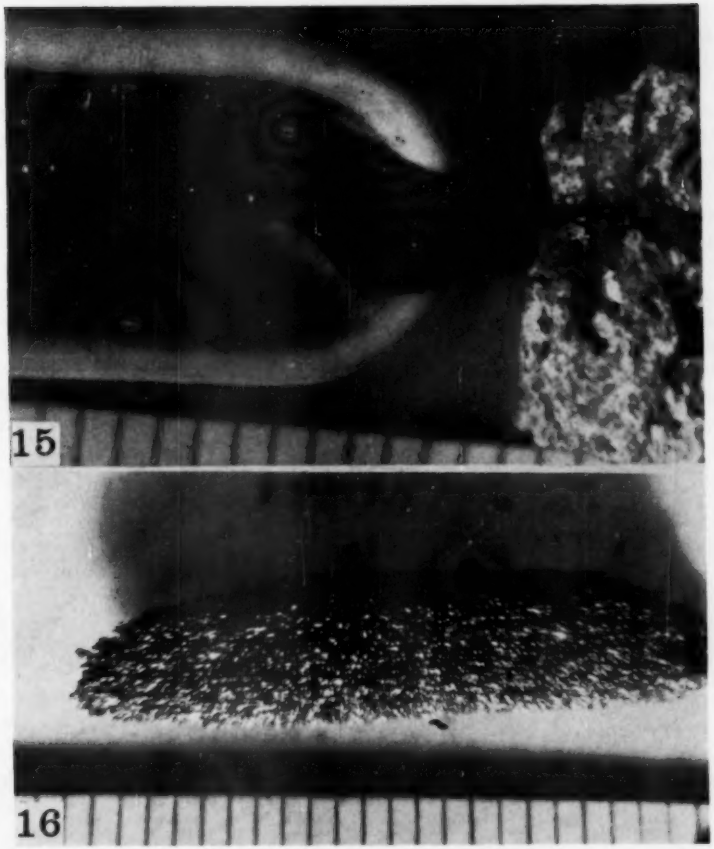

FIG. 15. Diffusion "flow" of copper sulfide onto fire-brick. Scale divisions millimeters.

FIG. 16. Dendritic crystals formed on the underside of a copper sulfide charge. Scale divisions millimeters.

Cobalt Sulfide.—In experiment G.B. 23 a massive intergrowth of linnaeite with chalcopyrite was used, with iron and copper sulfide as detectors. The charge was ground to a fine powder before firing, and afterwards it was found to have recrystallized. A number of small crystals on the sides and ends of the boat were suggestive of volatile transfer. These crystals were, however, too small to identify. There was little evidence of surface diffusion. X-ray fluorescence of the copper and iron sulfide failed to show any transfer of cobalt.

In experiment G.B. 31, small (0.1 to 1 mm) isolated crystals were found on the cooler end of the combustion boat. The larger ones were visually identified as chalcopyrite, but a borax bead test of the smallest ones showed that they contained cobalt, presumably transported by volatilization.

Nickel Sulfide.—Nickel sulfide melts at about 800° C. Prolonged heating at 750° C failed to change it in any way, beyond a slight surface tarnish on the crystals. Heated at about 800° C, the millerite partially melted, but there was no sign of volatilization onto the sides of the boat. Moreover, X-ray fluorescence of the detecting iron and copper sulfides failed to show any change in nickel content.

Chalcopyrite.—In experiments G.B. 26 and G.B. 27, chalcopyrite was formed, but there was no evidence of volatile transfer. This was corroborated by X-ray fluorescence methods in experiment G.B. 23 in which chalcopyrite was included with the linnaeite. No transfer of copper or iron was detected. Chalcopyrite dissociates at about 600° C in air. The chalcopyrite crystals found on the cooler end of the boat in experiment G.B. 31 were presumably precipitated from volatilized copper and iron sulfide. If so, this is an important evidence of volatilization of iron sulfide.

GENERAL DISCUSSION

The most surprising result of these experiments is the clear demonstration that copper sulfide will move at a fairly rapid rate down a temperature gradient above 450° C in the presence of small amounts of sulfur vapor. In the experiments described, migration produced a slag-like surface in some circumstances and crystal growth in others. Slag-like appearance suggests migration in a surface film.

None of the experiments conducted at temperatures below 675° C gave definite evidence of volatile transfer of copper unless the scant brownish material observed by Guy-Bray in some experiments at about the 500° C mark represents copper in some form. The substantial growth of copper sulfide and bornite crystals on the surfaces of test specimens and migration of copper sulfides into cracks appears to be best explained by solid diffusion. Since the presence of sulfur vapor is a critical factor in these movements of copper, it seems clear that they are in part, at least, surface phenomena. Similar phenomena have been referred to by some chemists and metallurgists as surface diffusion (4, 7), though it is by no means certain that all the adjustments occur in the surface films.

At temperatures above 675° C volatile transfer of copper may be of some importance where excess sulfur is present.

The migration of copper as copper sulfide into cracks in rock discs in Macdougall's experiments was probably partly governed by a drop in temperature from the copper sulfide into the rock disc. The copper sulfide, due to loss of sulfur, was porous and must have reached the temperature of the furnace atmosphere rapidly, whereas the rock discs, being composed of interlocking silicates with little pore space, was a poor conductor and reached the furnace temperature only gradually.

The FeS was more compact than the copper sulfide and a better conductor than the silicate discs, so it must have heated up at an intermediate rate.

The heating of the rock disc should, therefore, have taken place from both sides and the edges. The copper sulfide side was hottest from a very early stage and a steep temperature gradient must have existed from there to beyond the center of the disc. This accounts satisfactorily for the migration into cracks formed by differential expansion of the discs. Whether a descending gradient existed through the complete thickness of the disc at any time is not known because the relative heat conductivity between the FeS and silicate discs have not been determined.

Guy-Bray noted the presence of a few isolated crystals of copper sulfides at distances of up to 4 cm from the main mass of powder used in experiments at 700° and 1,000° (G.B. 19 and 21), and thought that this required volatile transfer. He thought it improbable that these formed by decrepitation of grains followed by reorganization to the crystal form by solid diffusion. There was no evidence of volatile transfer of copper below 675° C or of iron below 550° C. Volatile transfer at temperatures up to 1,000° C was only on a small scale. Since transfer did not occur in the absence of sulfur vapor, it appears that sulfide molecules of some kind were involved.

As shown by Figure 9, copper sulfide penetrated all available openings in the parts of the rock disc adjacent to the CuS pellet. Not only that, it must have exerted a certain force, pushing the walls of openings aside and moving fragments in open fractures to produce the isolated schist fragments and distortions within fragments that give the appearance of replacement where none had occurred.

CONCLUSIONS

1. Chalcocite or digenite at 450° C or at higher temperatures below the melting point and in the presence of sulfur at low pressures will move down a temperature gradient at a very appreciable rate.

2. The rate is increased if a stream of non-reactive gas containing sulfur is passed over it, moving down the temperature gradient. The presence of water vapor has no appreciable effect on the result.

3. If sulfur is absent, no movement occurs.

4. The movement below 675° C is apparently not due to volatile transfer. The material maintains continuity while changing its shape, so solid diffusion is indicated.

5. Movement of chalcocite into cracks in silicate rocks, as in Macdougall's experiments, probably occurred because a temperature gradient was set up due to porosity resulting from loss of sulfur by covellite and to differences in conductivity of the materials used during the heating cycle.

6. Structures and textures similar to those seen in some natural veins can be produced in the dry state by movement of copper sulfide down a temperature gradient. Ramifying veinlets with unsupported inclusions, replacement of pyrite by chalcocite, bornite, and chalcopyrite, and migration

of iron away from pyrite into vein fillings were interesting features in the experiments performed.

7. Some evidence of reaction of copper sulfide with iron-rich chlorite was obtained at 550° C, but calcite, siderite, biotite, epidote, bronzite and augite were unaffected under similar experimental conditions.

8. Evidence of volatile transfer of copper from copper sulfides at 675° C and higher, was obtained by both Meikle and Guy-Bray but this occurs only in the presence of sulfur vapor.

9. Volatile transfer of iron from pyrite can occur at temperatures as low as 550° C in the presence of sulfur vapor.

10. Minor volatile transfer of cobalt was indicated to occur at 1,000° C in the presence of sulfur vapor.

11. At 300° C or higher, copper and iron sulfide in contact with one another react to form intervening layers of bornite and chalcopyrite in the sequence chalcocite (or digenite)-bornite-chalcopyrite-pyrrhotite.

12. The thickness of reaction layers produced was approximately proportional to the square root of the time at a given temperature and increased with temperature. It is possible that a temperature gradient existed for a time within the test pieces. If so, this may have had some effect on the rate of transfer. The presence of water vapor or excess sulfur had little effect on these results.

13. Copper sulfide and magnetite in contact under similar conditions react similarly. Excess sulfur first converts magnetite to pyrite which then goes over to chalcopyrite and this in turn to bornite.

In all of these experiments, copper diffused much more rapidly than iron.

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McGILL UNIVERSITY,
MONTREAL, QUEBEC,
June 14, 1960

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ORE DEPOSITS OF THE BANNOCKBURN BASIN, LARDEAU-AREA, BRITISH COLUMBIA

BRUCE REED

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ABSTRACT

The Bannockburn Basin map-area in the Selkirk Mountains of southeastern British Columbia is underlain by Cambrian (?) metasediments. Two folds strike northwest; a tightly folded and slightly overturned anticline, and, on the northeast, a longitudinally faulted syncline. Reverse faults, contemporaneous with folding, were followed by a major longitudinal fault and a series of cross faults.

A bed of porous quartzite in the Marsh Adams formation contains disseminated galena and minor sphalerite, forming a mineralized zone called the Shelagh Vein, localized along the southwest limb and crest of the overturned anticline. The sequence of minerals, from oldest to youngest, in pyrite, sphalerite, galena, and tetrahedrite.

Mineralization of the Wagner claims is localized along faults. The Bannockburn claims contain galena, with some sphalerite and chalcopyrite, localized as a saddle reef in the lower limestone member of the Mohican formation.

INTRODUCTION

THE Bannockburn Basin, a glacial cirque in the Selkirk Mountains of southeastern British Columbia (Fig. 1) is part of the Lardeau area as mapped by Walker and Bancroft (3). The Shelagh vein of the Bannockburn Basin, although not productive at the present time, is of scientific interest as an example of localization of mineralization on a limb and crest of an anticline, and of replacement by sulfides of the calcite cement of a quartzite. As it

has in the past been a scene of active prospecting and may be so in the future, a record of the geological conditions may prove helpful.

The Bannockburn Basin Map-area covers about six square miles, between longitudes 117°07′ and 117°12′ and latitudes 50°37′ and 50°42′. A road leads along Healy Creek from the Lardeau River to the pass that separates the headwaters of Healy and Hall Creeks, at an elevation of 6,500 feet. From here the Basin is reached in the summer months by a jeep road.

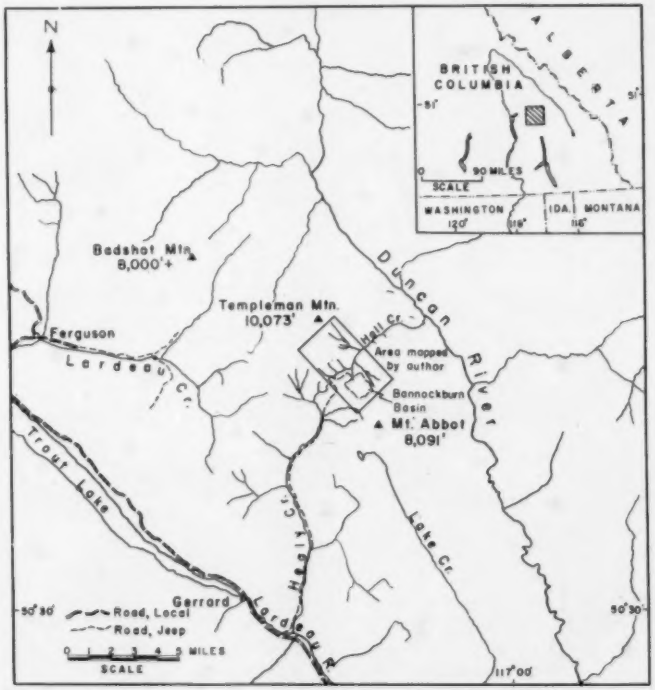

FIG. 1. Index map of Southeastern British Columbia showing the location of the Bannockburn Basin area.

Field work in the area was carried out during the summer of 1957. Field observations were plotted directly on a map (scale 1:6,000, contour interval 50 feet) prepared from aerial photos.

Accounts of previous geological work in the area may be found in a report by Walker, Bancroft, and Gunning (3).

ACKNOWLEDGMENTS

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Acknowledgment is also due to Mr. R. H. McConnel and Mr. A. E. Nugent of the Bunker Hill Company for their cooperation in supplying maps and equipment during the gathering of the data. Dr. G. E. P. Eastwood and Dr. James T. Fyles of the British Columbia Department of Mines acquainted the writer with the structures and stratigraphy of the region, aided in the interpretation of the geology, and were kind enough to read the

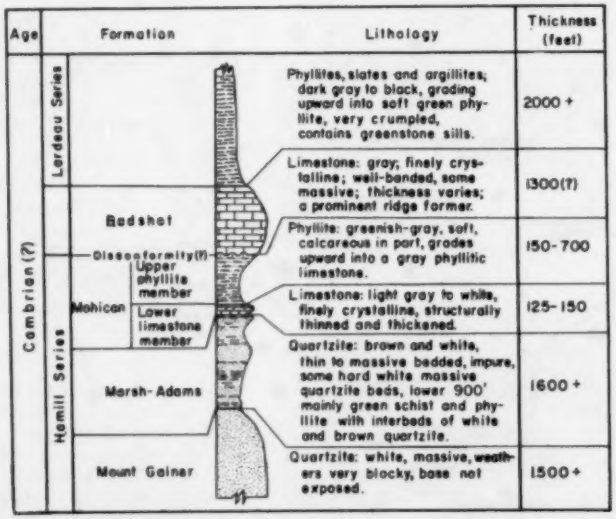
Age
Formation
Lithology
Thickness (feet)
Cambrian(?)
Hamill Series
Lardeau Series
Badshot
Disconformity(?)
Upper phyllite member
Mohican
Lower limestone member
Marsh-Adams
Mount Gainer
Phyllites, slates and argillites; dark gray to black, grading upward into soft green phyllite, very crumpled, contains greenstone sills.
2000 +
Limestone: gray; finely crystalline; well-banded, some massive; thickness varies; a prominent ridge former.
1300(?)
Phyllite: greenish-gray, soft, calcareous in part, grades upward into a gray phyllitic limestone.
150-700
Limestone: light gray to white, finely crystalline, structurally thinned and thickened.
125-150
Quartzite: brown and white, thin to massive bedded, impure, some hard white massive quartzite beds, lower 900' mainly green schist and phyllite with interbeds of white and brown quartzite.
1600 +
Quartzite: white, massive, weathers very blocky, base not exposed.
1500+

FIG. 2. Exposed rock formations in the Bannockburn Basin area.

manuscript. The writer is indebted to Joseph Gallo of Howser, British Columbia, for permission to publish this article. Mr. and Mrs. Edward Cannon, also of Howser, assisted in many ways that made completion of the mapping much easier.

STRATIGRAPHY

The rocks of the Bannockburn Basin area (Fig. 2) were mapped by Walker and Bancroft (3, p. 9) as the upper part of the Hamill series. These rocks were originally assigned to the Windermere system, which was considered to be late Precambrian. They are now thought to be lower Cambrian (?) (2, p. 164). In the Ferguson area, which lies six miles to the northwest, Eastwood (1) has subdivided the upper part of the Hamill series into the Mount Gainer (oldest), Marsh Adams and Mohican formations. The

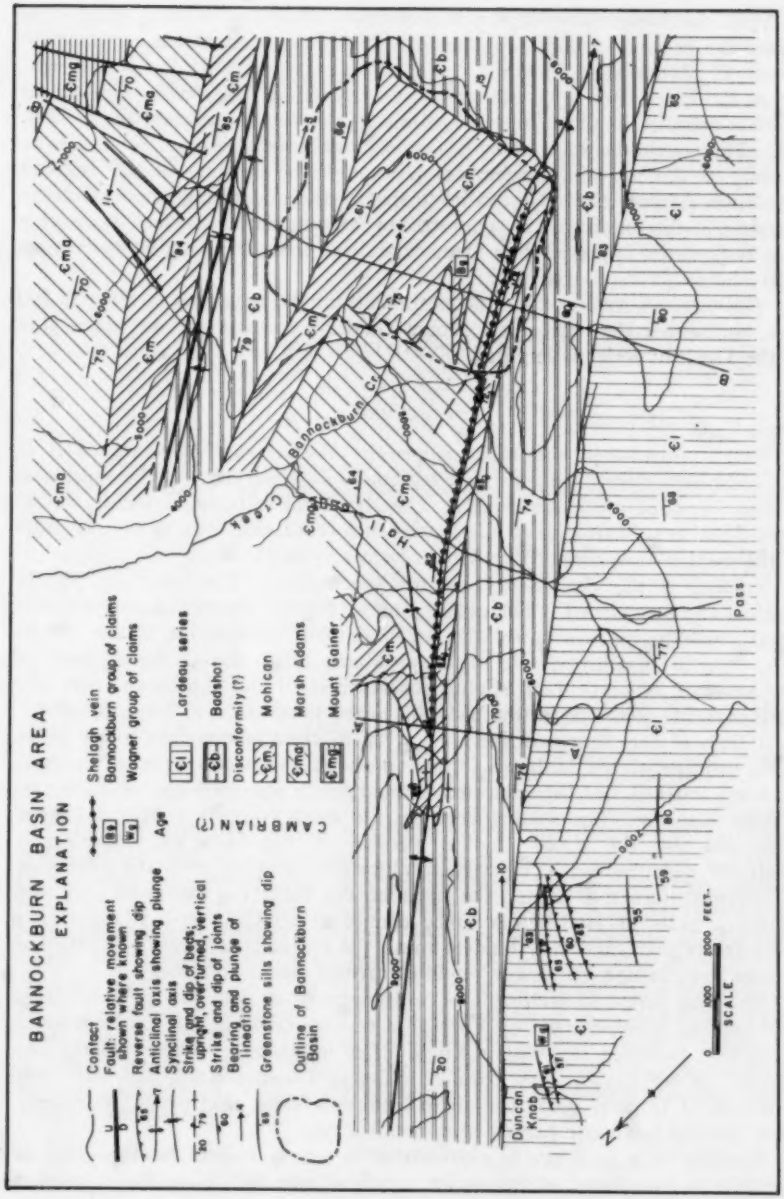
BANNOCKBURN BASIN AREA
EXPLANATION
Contact
Fault, relative movement shown where known
Reverse fault showing dip
Anticlinal axis showing plunge
Synclinal axis
Strike and dip of beds, upright, overturned, vertical
Strike and dip of joints
Bearing and plunge of lineation
Greenstone sills showing dip
Outline of Bannockburn Basin
Shelagh vein
Bannockburn group of claims
Wagner group of claims
Age
CAMBRIAN (?)
Cl Lardeau series
Cb Badshot
Disconformity (?)
Cm Mohican
Cma Marsh Adams
Cmg Mount Gainer
Bannockburn Cr.
Creek
Hall
Duncan Knob
Pass
SCALE
1000 2000 FEET
N

FIG. 3.

rocks in the Bannockburn Basin have been correlated with those mapped by Eastwood in the Ferguson area, and the same formation names are used for the subdivided Hamill series.

A brief description of the lithology is given in Figure 2. The upper phyllite member of the Mohican formation is thicker to the northeast (Fig. 4). This could be due either to depositional thickening or to a disconformity at the top of the member. Although the bedding in the Badshot formation is approximately parallel to that in the underlying upper Mohican member, a disconformity is suggested by an undulating surface truncating thin beds of the upper phyllite member and by presence of a thin rusty zone of oxidation at this horizon (?).

The total thickness of the metasediments in the map-area is about 7,100 feet, but neither the base of the Mount Gainer formation nor the upper part of the Lardeau series is exposed.

STRUCTURE

The Lardeau-area was first mapped by Walker and Bancroft (3). It is a complexly folded sequence that regionally dips and faces to the southwest (Fyles, personal communication). The structural features of the Bannockburn Basin area have a prevailing north-northwest trend, although cross faults in the southeastern part of the map strike nearly east (Fig. 3).

Folding is the prominent type of deformation. The folds are tightly pinched and overturned. The geologic map (Fig. 3) shows two major folds: an anticline to the southwest and an accompanying syncline to the northeast. On the southwest side of Bannockburn Basin the southwest limb of the anticline is vertical or slightly overturned to the southwest. On the northeast side of the Basin the beds dip to the northeast and form the southwest limb of the next syncline. In areas of tight folding the lower limestone member of the Mohican formation shows evidence of plastic flowage. In many cases it has been thinned or completely squeezed out of its stratigraphic horizon. The folding between the more competent Mount Gainer formation and the upper phyllite member of the Mohican formation is gradually disharmonic. This structural pattern coupled with the effects of topography does not permit the axes of the folds on the northwest and southeast sides of Hall Creek to be connected on the map. Many minor folds are present, and they tend to mask the major structures. In areas of intense deformation the softer phyllites are crumpled and sheared.

The first period of faulting was contemporaneous with the major folding. The faulting is represented by a series of reverse faults in the Lardeau series 3,000 feet southeast of Duncan Knob. The faults strike northwesterly and dip 50° to 80° SW. Two parallel faults at Duncan Knob and one fault southeast of Duncan Knob contain galena, sphalerite, and pyrite; elsewhere these reverse faults are barren of mineralization.

Faulting of a later age is represented by a longitudinal fault parallel to and 200 feet northeast of the major synclinal axis in the southeast portion of the map. The dip and the exact amount of displacement of the fault are

not known. Although the full thickness of the Badshot formation is 1,300 feet, the maximum thickness on the northeast side of the faulted syncline is only 600 feet. This suggests cutting out of part of the formation by a fault along which the northeast block was (relatively) elevated. Effects of the fault are evident also from difference in plunge of folds on opposite sides of it; on the southwest side the plunge is 7° SE; on the northeast side it is 9° NW.

Jointing is displayed in the Badshot formation where it crops out as a prominent ridge along the entire west portion of the map-area. The joints strike perpendicular to the axes of the major folds and dip steeply to the

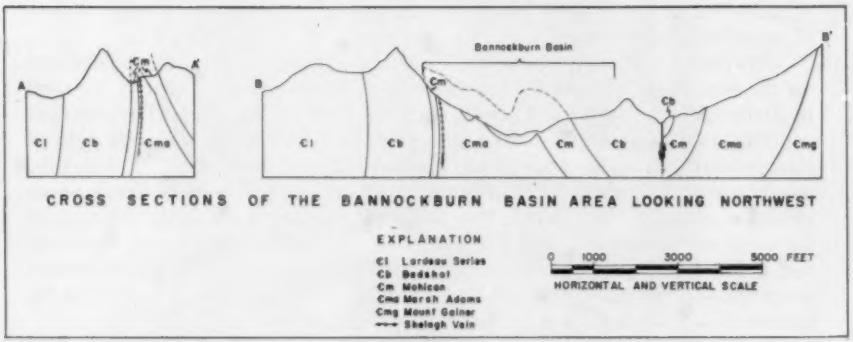

FIG. 4.

northwest. They apparently are extension joints resulting from a slight elongation parallel to axes of the folds.

ORE DEPOSITS

The Lardeau area was first prospected in the 1880's, and since that time interest has varied from periods when work was practically nil to periods of intensive prospecting, the chief interest being centered around the lead-silver deposits. Numerous mining claims in the Bannockburn Basin have been worked in a desultory manner since the late eighteen hundreds. Recently the discovery of a low-grade disseminated lead deposit, called the Shelagh Vein, first found in the Marsh Adams formation along the west side of Bannockburn Basin, has renewed interest in the area. In addition to the description of the Shelagh Vein, the Bannockburn and Wagner claims are briefly mentioned here as they both show sizeable amounts of galena in the surface exposures and have served as the primary interest for exploration through the past years.

Shelagh Vein

General Description.—The Shelagh Vein is a disseminated lead deposit localized in a hard brown limy coarse-grained porous zone of a 40-foot thick

quartzite bed in the upper part of the Marsh Adams formation. Mineralization is concentrated as one or more bands of disseminated galena that average less than 4 feet wide. Within these bands small fractures, rarely exceeding one-half inch in width, are generally filled with quartz, but some are filled with galena and minor amounts of sphalerite. These fractures may extend a few feet into the stratigraphically higher and lower beds from the mineralized bands. Traces of disseminated mineralization extend 8 to 10 feet on either side of the mineralized bands. The 40-foot thick quartzite bed contains disseminated pyrite which upon weathering gives a rust-flecked appearance to the rock. The mineralized quartzite shows no gossan staining or discoloration, and the presence of sulfides is disclosed only on a fresh surface. Weathering of the coarser zones of the quartzite produces a rough surface of rounded quartz grains.

Structural Location of the Ore.—Mineralization of the bed is localized on the southwest limb and crest of the overturned anticline that is exposed in Bannockburn Basin and north of Hall Creek (Fig. 3). The heaviest concentration of sulfides occurs south of Hall Creek along the west side of Bannockburn Basin at elevations between 6,000 and 6,500 feet. Below this, minor mineralization is found where the quartzite crosses Hall Creek at an elevation of 4,475 feet. From this point the sulfides increase up dip toward the crest of the anticline. In one case minor sulfides continue over the crest and a few feet down on the northeast limb. Examination of the favorable quartzite bed in other structural positions in the map-area proved it to be barren of sulfides except for a few pyrite crystals.

Small faults are present where the quartzite is tightly folded; two of them (too small to be shown on the map) offset the quartzite along the west side of the Bannockburn Basin but neither shows any mineralization. Minor fractures within the quartzite are, however, in places filled with galena.

Concentration in the crest and southwest limb of the anticline implies that the sulfides were introduced after folding was well advanced if not, in fact, after its completion. As it seems plausible that ore-bearing solutions ascended along one limb of the anticline, their continued path would presumably have been upward along the plunge. There is no definite evidence as to their ultimate point of exit, which may conceivably have been through fissures into the Badshot formation.

Mineralogy.—In the Shelagh Vein, sulfides, chiefly galena, form fillings between quartz grains in the quartzite.

The vein mineralogy consists chiefly of quartz but contains minor amounts of muscovite, siderite, chlorite, and limonite. The quartz grains are well rounded and have an average diameter of 0.6 mm as measured in two specimens. Where the rock is unmineralized, the quartz grains are cemented by both quartz and calcite and it is significant that the 40-foot bed is the only one in the Marsh Adams formation in the area with enough carbonate to effervesce with acid, a characteristic that serves to distinguish it from other quartzite members in the Marsh Adams formation. Generally the amount of calcite does not exceed 15 percent although in one specimen it reached 40 percent.

Where there is mineralization calcite is rare. The inverse relationship between calcite and sulfides is indicated by samples taken for the purpose of comparing mineralized and unmineralized rock. In two samples sulfides are seen partially replacing calcite and the fact that in most cases the sulfides are fillings between quartz grains, together with the fact that in places calcite is absent and sulfides constitute the interstitial material, is taken as evidence that in well-mineralized material this replacement is complete.

FIG. 5. Typical ore of the Shelagh vein. Galena (white) occurs as small fillings between quartz grains and replacing calcite. × 100.

The metallic minerals are pyrite, sphalerite, galena and tetrahedrite. In one specimen a small inclusion of chalcopyrite was seen in the sphalerite. Assays indicate a small amount of silver in the ore but as no silver mineral was observed it is concluded that the silver is in solid solution in either the galena or tetrahedrite or both.

Pyrite is generally present as small euhedral or subhedral grains disseminated throughout the mineralized portion of the quartzite. In many cases the pyrite contains small fractures filled with sphalerite or galena and

it is replaced by both of these minerals. Pyrite was the first sulfide to be deposited in the sequence of mineralization.

Sphalerite is present in minor amounts in all of the specimens examined. Internal reflection reveals the presence of two varieties of sphalerite; a clear, pale-yellow variety (yellow jack), and a bright-reddish type (ruby-jack). Many grains, however, show no internal reflection. The sphalerite replaces pyrite and is replaced by galena.

Galena is the most abundant sulfide. It occurs both as interstitial fillings and as a replacement of the calcite that surrounds the quartz grains (Fig. 5). Individual galena grains are small, generally averaging less than 0.05 mm in diameter. The galena replaces pyrite and sphalerite, and in many cases contains incompletely replaced rounded inclusions of sphalerite. The edges of galena grains are serrate under high magnification and tongues of tetrahedrite project into the galena.

Tetrahedrite is present in nearly all of the specimens examined, it appears to have been deposited after the galena. Irregular veinlets of tetrahedrite traverse the galena, and in many cases the tetrahedrite shows straight edges and angles parallel to the cleavage of the galena.

The paragenetic sequence of the ore minerals is pyrite (oldest), sphalerite, galena, and tetrahedrite. This is somewhat in disagreement with the sequence of crystallization of the ore minerals as indicated by Gunning (3, p. 115). He gave the following paragenetic sequence for the Lardeau map-area: "pyrite, sphalerite, gray copper (and chalcopyrite), and galena." He mentions the possibility that tetrahedrite and galena could have been in part contemporaneous and noted one case of tetrahedrite occurring as fine veinlets in galena. Without questioning his paragenetic sequence for the Lardeau area, the writer feels that the evidence points to a different sequence of crystallization for the Shelagh Vein.

OTHER PROSPECTS

Wagner Group.—The Wagner group of claims is in the northwest part of the map area. A report of the workings is given by Gunning (3, p. 79–80). The claims are in the Lardeau series, the rocks are slates and phyllites with many segregations of white vein quartz. An adit, now caved, was driven along a fault on the southeast side of Duncan Knob. Limited investigation of the adit shows segregations of quartz, carrying pyrite, galena, and sphalerite, localized along the hanging wall of the fault. A series of faults 3,000 feet southeast of Duncan Knob contain minor amounts of galena and pyrite. Other veins of quartz, apparently controlled by minor shear zones associated with the main faults also contain sulfides.

Bannockburn Group.—The Bannockburn group of claims lie within the Bannockburn Basin. Good surface exposures of galena incited old-time prospectors to drive a shaft, an adit, and numerous open-cuts to find the underground extension of the encouraging surface showings. All underground workings have caved; but Gunning (3, p. 77) gives a description of the claims. Examination of the surface showings indicates that the ore is

controlled by a narrow pencil-shaped saddle reef along the crest of a drag fold between two beds in the lower limestone member of the Mohican formation. Mineralization consists of masses of galena with minor amounts of pyrite, sphalerite and chalcopyrite. The gangue is quartz and calcite. It appears that the sulfides, supplied by solutions ascending along fractures, were localized by replacement and cavity filling in the receptacle at the crest of the drag fold.

Origin of the Ore

Walker, Bancroft, and Gunning (3, p. 31 and 115) believe that the metalliferous deposits of the Lardeau map-area were formed by ascending heated solutions that originated during the final stage of consolidation of the magmas that gave rise to the igneous rocks that border the district to the north, west, and south. Some ores in dikes close to the Kuskanax batholith could have some genetic tie with the igneous masses. As the deposits in the map area are 14 miles from any outcrop of granitic rock the source of its mineralization is less definitely indicated. It is evident that the Shelagh Vein is an epigenetic deposit formed from hot ascending solutions and the writer prefers to leave the source of the metals open to question, and only to suggest that the coarser grained, and presumably, more porous and permeable bed served to localize the mineralizing solutions.

GEOLOGICAL MUSEUM,
HARVARD UNIVERSITY,
May 27, 1960

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THE PYRITE BODY AND COPPER OREBODIES CERRO DE PASCO MINE, CENTRAL PERU

HECTOR J. WARD

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ABSTRACT

The general geology of the Cerro de Pasco Mine in Central Peru is briefly reviewed to acquaint the reader with the setting of the large body of pyrite and associated orebodies. The Pyrite Body is about one mile long, up to a quarter of a mile wide and extends downwards for more than half a mile. Three main types of pyrite namely "hard pyrite," "soft pyrite" and "pyrite breccia" probably represent the effect of replace-

ment of different beds of limestone. Relict sedimentary structures show that the Pyrite Body is structurally controlled and that at least ninety per cent of the Body represents replaced sediments. The veins in the Pyrite Body and surrounding rocks probably belong to one period of deformation and seem to fit into a pattern of wrench fault tectonics. Supergene and hypogene copper orebodies in the Pyrite Body are localized by chemical, lithological and structural factors.

CERRO de Pasco Mine on the western side of Cerro de Pasco township is at 10°42′ south latitude and 76°15′ west longitude (Fig. 1) in Central Peru. The collar of the main shaft, Lourdes shaft, is at 14,200 feet above sea level.

FIG. 1. Locality map.

The writer, who was at Cerro de Pasco during the period 1953–1955, in addition to routine duties, had the privilege of studying one of the largest masses of pyrite in the world. The purpose of this paper is to describe the enormous mass of pyrite, which is the home of at least fifty copper, and many lead-zinc and silver orebodies, any one of which could, in itself, have constituted a mine. This contribution to the geology of Cerro de Pasco is presented in order to modify earlier ideas that the pyrite mass and the ore-

bodies are not controlled by bedding (12) and to suggest that the veins with which the copper orebodies are associated were formed at the same time as wrench faults in the area.

The origin of the Pyrite Body is not discussed, as the writer is of the opinion that no evidence has yet been found to contradict its postulated epigenetic origin.

PREVIOUS WORK

The geology and ore deposits of the Cerro de Pasco mine have been described by McLaughlin et al. (12), by Bowditch (2), and by the Cerro de Pasco Corporation Geological Staff (5). Lacy (9) described the different types of pyrite and their relations to mineralization. Graton and Bowditch (3) discussed the acidity and alkalinity of the ore-bearing solutions. The Matagente lead deposit about half-a-mile northeast of Cerro de Pasco has been described by Amstutz and Ward (1).

The geological map (Fig. 2) prepared by the writer incorporates work carried out by Jenks (7) who outlined the stratigraphy of the area and Johnson et al. (8) who dealt in detail with the ore deposits and geology of the Atacocha district 15 km to the north-northeast of Cerro de Pasco.

ACKNOWLEDGMENTS

The writer wishes to thank the Cerro de Pasco Corporation for permission to publish this paper. Dr. G. C. Amstutz, formerly of Cerro de Pasco Corporation now of Missouri School of Mines, confirmed the sedimentary origin of some of the textures and structures in the pyrite by laboratory work. He also discussed many aspects of Cerro Geology with the writer. The friendship and help of many Cerro de Pasco geologists, notably M. Bernstein, K. W. B. Iten, R. L. Meyer, A. Velasquez, and T. Volker will be long remembered. Invaluable suggestions from Alberto Terrones are acknowledged with pleasure. Dr. Frank Simons of the U. S. Geological Survey kindly loaned the writer airphotographs that were of great assistance in reconnaissance mapping. Discussions with Dr. Charles F. Park Jr. of Stanford niversity were encouraging and stimulating. The writer is indebted to Professor R. T. Prider, University of Western Australia for critically reading the manuscript.

The sections and plans compiled by the writer are based on the results of geological mapping carried out by geologists of the Cerro de Pasco Corporation since 1917. However the views expressed herein are not necessarily those held by the geological Staff of Cerro de Pasco Corporation.

DESCRIPTIVE GEOLOGY

The general geology of the environs of the mine is reviewed to acquaint the reader with the setting of the large pyrite body and associated orebodies at Cerro de Pasco.

The oldest rocks are highly contorted slates, phyllites and quartzites of the Excelsior Formation. No fossils have been found in the formation but Newell et al. (14) have assigned it to the Devonian on lithological evidence.

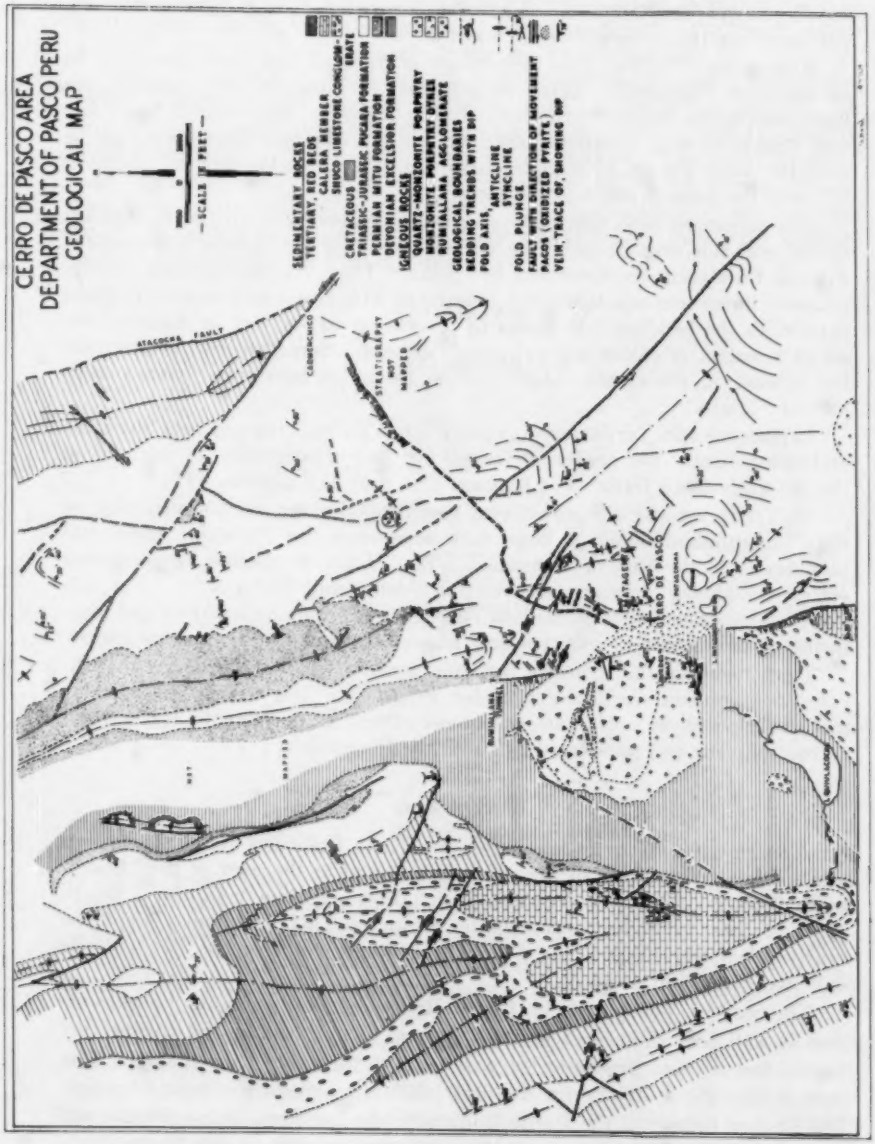

FIG. 2. Cerro de Pasco area, Department of Pasco, Peru. Geological map.

The Permian Mitu Formation overlies the Excelsior rocks unconformably. In the vicinity of Cerro de Pasco the formation is a conglomerate with pebbles of quartz and argillaceous material.

Throughout Central Peru limestones of Jurassic age unconformably lie on the Mitu Formation. Harrison (6), and McLaughlin (11) grouped the limestones as the Pucara Formation. In the Cerro de Pasco district Jenks (7) was unable to map separately the Jurassic and Triassic limestones; so he used the name Pucara to include Jurassic and Triassic limestones. Johnson followed the same practice at Atacocha.

The limestone beds that have played a prominent role in the localization of the lead-zinc ores probably lie within zone 2 of the eastern facies of the Pucara Formation as described by Jenks. They are thin-bedded, sandy-textured limestones and light-gray limestones with layers and nodules of chert parallel to the bedding. Boulders of breccia up to six feet in diameter are set in a matrix of calcite and calcareous cement. Some breccias are tectonic but others(in the mine), which will be discussed later, may have a sedimentary origin.

Cretaceous and Tertiary sedimentary rocks do not crop out near the mine and consequently the reader interested in their stratigraphy is referred to the descriptions of Jenks (7), Johnson (8), and McLaughlin (11).

In Tertiary times a volcanic vent was formed along the western edge of the "Longitudinal" fault, a large fault separating the Excelsior slates and phyllites from the Pucara Formation. Well-stratified volcanic agglomerates occupy the almost circular vent, which is about a mile in diameter. The volcanic agglomerate, called Rumillana Agglomerate, contains boulders and fragments of sedimentary rocks, volcanic glass, and fine-grained igneous rocks.

Intrusive into the eruptive volcanic material are a fine-grained flesh-colored fragmental rock, the Lourdes Fragmental and a light-gray quartz monzonite-porphyry. Narrow monzonite dikes of porphyritic texture cut across the vent and pass eastwards into the limestone.

PYRITE BODY

A large mass of pyrite known as the Pyrite Body lies along the eastern and southeastern margin of the volcanic vent and to the west of the "Longitudinal" fault. Mine workings and diamond drilling show it to have a length of more than 5,000 feet, a maximum width of 1,200 feet and a depth of nearly 3,000 feet (Figs. 3, 4, 5). The average width of the Pyrite Body is between 400 and 450 feet.

The western contact of the Pyrite Body with the rocks of the volcanic vent is well-defined in most places. A zone of pyritization and silicification several feet wide is present in the wall rocks to the west of the contact. The contact dips about 70° W for the first 1,000 feet and then is nearly vertical. The eastern contact of the Pyrite Body with the limestone is transitional and in many places difficult to map. The southern contact of the Pyrite Body with the Excelsior Formation is well-marked.

Types of Pyrite.—Six distinct ages of pyrite have been found by laboratory studies (9) but only a few of them can be distinguished as mappable units in the mine. Apart from the main body of pyrite, pyrite is the major sulfide mineral in the veins and veinlets cutting the Pyrite Body.

The pyrite of the Pyrite Body may be fine to coarse-grained dense massive pyrite ("hard pyrite"), friable sandy-textured pyrite ("soft pyrite"), or friable sandy-textured pyrite with fragments and boulders of "hard pyrite" or altered sediments. This latter type of pyrite is known as "pyrite breccia." The "pyrite breccia" is known as "microbreccia" where the degree of brecciation is microscopic. The "soft pyrite" and "pyrite breccia" are predominantly along the eastern side of the Pyrite Body where they form a southeastern extension in the Pucara Formation.

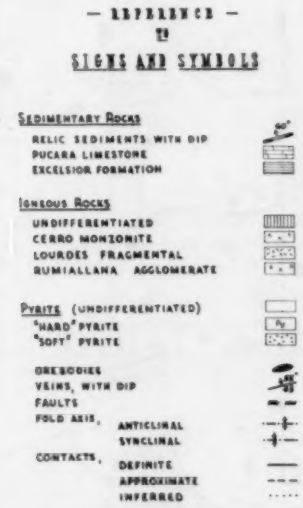

FIG. 3. Reference to signs and symbols.

The "hard pyrite" and "soft pyrite" probably represent the effect of replacement of different beds of the eastern facies of the Pucara Formation (1) by iron sulfide. Pyritization of thin-bedded sandy-textured limestone probably produced thin-bedded sandy-textured pyrite. "Hard pyrite" with chert may be the pyritized equivalent of massive limestone with chert horizons.

"Pyrite breccia" in some instances is pyritized brecciated limestone.

"Microbreccia" has an economic significance as it is a host to high-grade lead-zinc ores. The grain size of the "microbreccia" and the interlocking of galena and sphalerite are such that difficulty in their separation is encountered in the grinding and flotation circuits at the Paragsha Concentrator.

The origin of the "microbreccia" has not been completely solved. In the southeastern limb of the Pyrite Body the "microbreccia" ores are layered

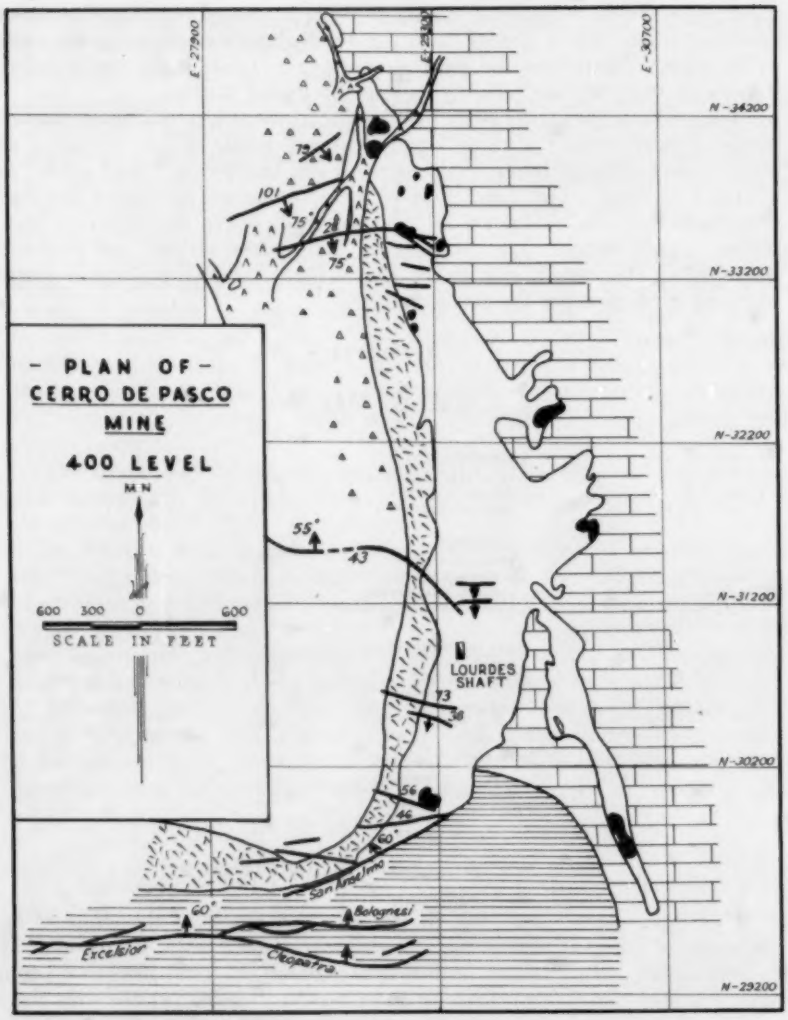

FIG. 4. Plan of 400 level, Cerro de Pasco Mine.

and contain discontinuous bands of clay. In stopes on the 1200-foot level the "microbreccia" ores follow the northeasterly trend of unreplaced sediments in the Pyrite Body (Fig. 6) and thus the "microbreccia" ores seem to be the result of the replacement of breccia horizons, which may have been sedimentary or intraformational in the limestone.

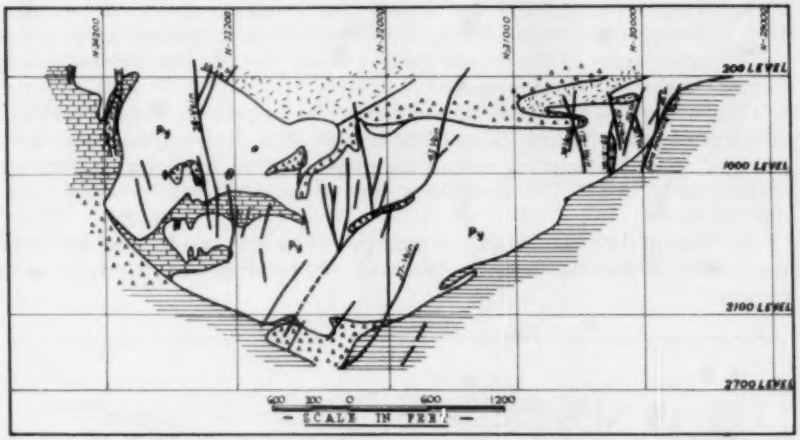

FIG. 5. Longitudinal section through the Pyrite Body at E29100, Cerro de Pasco Mine.

Nature of the Replaced Rocks.—The type of rock replaced by the Pyrite Body is economically important because the shape of the body is largely controlled by the structures and textures of the pre-existing rocks. Primary copper orebodies are in areas of "hard pyrite" and secondary copper orebodies are in "soft pyrite" near lead-zinc orebodies.

Early workers (12, 5) considered that a greater part of the Pyrite Body had replaced igneous rocks and that it was not concordant with sedimentary

FIG. 6. Plan of part of 1200 level showing relation of "microbreccia" type lead-zinc ore to the trend of relict sediments, Cerro de Pasco Mine.

rocks. Lacy (9) suggested that areas of barren pyrite and pyrite mineralized with copper are replaced volcanic rocks, and the remaining areas along the eastern margin of the Pyrite Body (where the lead-zinc orebodies are located) are replaced limestones.

The writer did not have the opportunity to inspect all mapped sections of the mine owing to lack of complete access. The observations made indicate that at least ninety per cent of the pyrite resulted from the replacement of limestone. A. J. Terrones,[1] in a personal communication, agrees with this conclusion.

Bedding in the "hard pyrite" is difficult to find probably because intensive pyritization of massive limestone obscured any bedding that may have been present.

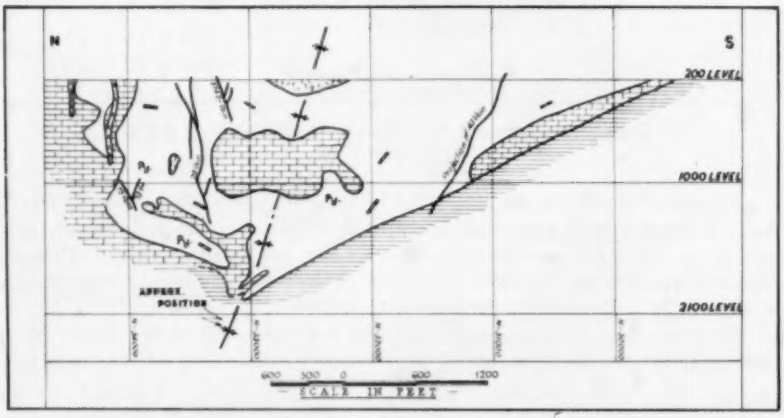

FIG. 7. Longitudinal section through the Pyrite Body between point N34200, E29100 and point N29200, E30100 showing trends of relict sediments and the approximate position of the axial plane of crossfolding.

Bands of unreplaced sediments in the Pyrite Body were traced to within a few feet of the western contact of the Pyrite Body with the Rumillana Agglomerate. No chert was observed in the agglomerate that could be equivalent to chert in the pyrite. Stratification planes are not continuous over any great distance in the agglomerate in which the fragments vary in size up to more than six inches in diameter.

In the lower levels of the mine the Pyrite Body is surrounded by volcanic agglomerate. This does not necessarily mean that pyrite replaced agglomerate. The vent was formed before the Pyrite Body, and consequently the pyrite may have replaced limestone partly enclosed by agglomerate.

The well-defined nature of the contact between the Pyrite Body and the volcanic rocks, the relative absence of relict structures and textures of volcanic rocks in the pyrite, the absence of chert in the volcanics, and the con-

[1] Formerly Assistant Chief Geologist, Cerro de Pasco Corporation.

tinuity of bands of unreplaced sediments to the contact of the Pyrite Body with rocks of the vent, indicate that the pyrite replaced only a small portion of the igneous rocks.

Structure of the Pyrite Body.—In long section (Fig. 7) the body of pyrite is trough-shaped. At its southern end a cross-section of the Pyrite Body is broadly anticlinal in form. Northwards the eastern limb disappears leaving only a thick western limb.

Unreplaced sediments in the southern part of the Pyrite Body are folded along north-trending axes. The folds plunge 30°–70°N. In the northern portion of the pyrite body the folded sediments plunge to the south (Figs. 7, 8). Some sedimentary beds are folded along east-trending axes.

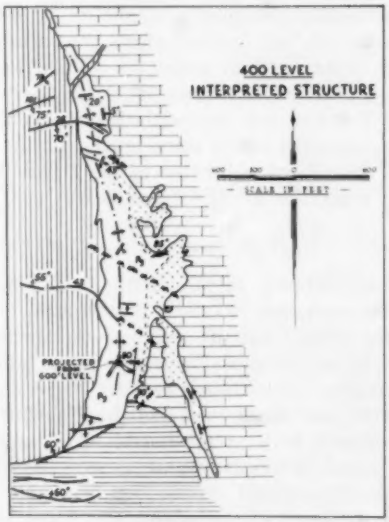

FIG. 8. 400 level, interpreted structure.

The attitude of the sediments indicates that pyrite replaced crossfolded sediments or was folded along an east-trending axis after replacement of the sediments.

The timing of crossfolding bears on the continuity of the Pyrite Body in depth. If pyrite replaced crossfolded sediments, the channelways along which the sulfide-bearing fluids migrated possibly continue in depth. On the other hand, if pyrite replaced the limestone before crossfolding then the point of entry of the fluids, which introduced the pyrite, was probably destroyed by folding and faulting. As the veins and orebodies post-date the Pyrite Body the channelways for the ore-bearing fluids may still be preserved, but copper orebodies that are related to the veins may not be present owing to the absence of pyrite in depth.

Sulfide Masses in the Pyrite Body.—Pipe-like bodies of pyrrhotite, lead-zinc copper, and silver minerals have been disclosed by mine development.

Pyrrhotite bodies in the mine are near masses of unreplaced and altered sediments. They do not seem to be related to the vein systems and probably formed at the same time as the Pyrite Body (9). Cassiterite has been found in small amounts in one mass of pyrrhotite.

Lead-zinc ores occur as replacement bodies in sediments and as large pipes in the Pyrite Body. Some orebodies are controlled by the attitude of replaced and unreplaced sediments in the Pyrite Body. Others are formed by the splitting up of lead-zinc veins in the narrow parts of the Pyrite Body and by replacement of "hard pyrite" by galena, sphalerite, and pyrite along the veins. The lead-zinc orebodies were probably formed during the second period of mineralization that took place after the formation of the vein systems.

Silver orebodies are in "soft pyrite" along the eastern side of the Pyrite Body. The largest silver orebody is in the Pyrite Body near its contact with the limestone. This orebody plunges to the north at the same angle as the contact of the Pucara Limestone with the Excelsior Formation. Silver orebodies seem to be localized where veins break up near lenses and bands of partly replaced and unreplaced sediments in the Pyrite Body.

Pipe-like copper orebodies are discussed below.

STRUCTURAL GEOLOGY

Detailed geological mapping of the district will have to be carried out before an accurate account can be given of the stresses that produced the fracture pattern of the district and the vein systems of the mine.

Structures (Fig. 2) of the post-Palaeozoic rocks were mapped with the aid of aerial photographs. Much work remains to be done, especially in determining the structure and stratigraphy of the Excelsior Formation.

Folds.—The dominant folds trend north. The regional plunge of the folds is 5°–15° S. Local reversals in plunge occur.

A domal structure is exposed on the southern side of Cerro de Pasco township and to the southeast of the mine. On either side of the dome are synclines. The axis of one syncline, the Matagente Crossfold (1) plunging 30°E varies in strike from E–W to N60°E. The Matagente Crossfold continues westwards through the Cerro de Pasco Mine where its presence is evidenced by reversals in the plunge of folds in unreplaced sediments. The syncline on the southern flank of the dome strikes N40°W and plunges 20°SE. Half a mile to the south of Lourdes shaft a syncline in Tertiary rocks plunges to the south at 5°. In the vicinity of the shaft unreplaced sediments plunge to the north indicating that an anticlinal crossfold axis, possibly the westward continuation of the long axis of the domal structure, is on the western side of the "Longitudinal" fault south of Lourdes shaft.

Johnson (8) has mapped two minor fold axes north of the road to Huanuco and about halfway between Cerro de Pasco and Carmen Chico. One fold axis strikes about N60°E and the other strikes N45°W. The minor folds and the reversals in the plunge of the folds were probably formed at the same time as the domal structure.

Faults.—A reverse fault that strikes N10°W and dips steeply east separates the Excelsior Formation from the Pucara Limestone (7). This fault known as the "Longitudinal" fault has been mentioned (5) as playing a part in the localization of the volcanic vent. Jenks (7) considers that the "Longitudinal" fault was developed when the sediments were folded along north-trending axes. The position of the fault is difficult to determine in the mine workings.

Numerous faults in the district, which are prominent in the Pucara Limestone and Tertiary rocks but indistinct in the Excelsior Formation, strike N45°–65°W and dip vertically. At Carmen Chico a large N45°W fault displaces a reverse fault parallel to the "Longitudinal" fault and near the Rumillana Tunnel a N65°W fault displaces the "Longitudinal" fault. Thus the N45°–65°W faults are younger than the "Longitudinal" fault.

TABLE 1

THEORETICAL WRENCH FAULT, THRUST FAULT AND FOLD DIRECTIONS AT CERRO DE PASCO BASED ON $\beta = 30°$, $\gamma = 15°$

Right- or left-lateral wrench fault		Thrust or fold direction
RL N60°E	First order	N-S
LL N60°W		
RL N15°W	Second order	N45°W
RL N75°E		N45°E
LL N75°E		
LL N15°W		
RL N60°W	Third order	E-W
RL N60°E		
RL N30°W		
RL N30°W		
LL N60°W		N-S
LL N60°W		
LL N30°E		
LL N30°E		

The direction of displacement on the N45°–65°W faults is north side west. The faults are regarded as first-order, left-lateral, wrench faults formed by compression in the later stages of folding. Several faults that strike N30°E are probably complementary third-order, right-lateral, wrench faults. Second-order right- and left-lateral wrench faults are probably represented by N15°–30°W faults.

The Matagente Crossfold persists westwards into the mine and this suggests that it is younger than the "Longitudinal" fault. As no crossfolds seem to cut the northwesterly faults they were probably formed at the same time as the wrench faults and consequently the domal structure and its flanking synclines may be interpreted as third-order dragfolds developed during wrench faulting.

In general the angle between wrench faults and the compressive stresses is variable (13). Theoretical directions of wrench faults, thrust faults and fold directions at Cerro de Pasco based on the assumptions (1) $\beta = 30°$, $\gamma = 15°$, are listed in Table 1.

Moody and Hill (13) consider that the value of the angle γ which is the angle second-order anticlines or thrust faults make with the parent or first-order shear has not been satisfactorily determined. The value of γ may range from 5° to 30° with an average value of 15°. Any variations in the homogeneity of the rocks subjected to compression will also cause variations in the value of γ.

A complete picture of the faults in the Cerro de Pasco district cannot be gained unless the veins, which are mineralized fractures, are considered. At Atacocha (8) the dacite dikes associated with the period of mineralization have been intruded along northwesterly faults. At Milpo, which is south of Atacocha, the dacite dikes, in places, gradually change into mineralized fractures. The fractures, which are now veins, and the northwesterly faults may have developed simultaneously at Cerro de Pasco.

Faults younger than the veins have been mapped in the mine but have not been fully studied. A hinged reverse fault and another set of faults striking N45°–50°W offset the Cleopatra vein system. The faults are not persistent along their strike.

VEIN SYSTEMS

The copper-bearing veins near the eastern and southern margin of the vent can be grouped into northern, central, and southern vein systems.

Central Vein System

The main vein of the system is the 43 vein. It is situated centrally with respect to the major veins of the other systems.

The 43 vein has an average strike of N60°W above the 1,000-foot level and a dip of 55°N. The dip varies from 30°N to 75°N. The most pronounced change in dip is between the 1,000-foot level and the 1,400-foot level along the contact of the Pyrite Body and the volcanics where the vein flattens to 30°N on entering the Lourdes Fragmental. The vein resumes its normal dip where it re-enters the Pyrite Body below the 1,400-foot level. The strike of the vein varies between N45°W and N80°W. In the Pyrite Body the strike is more northerly than in the igneous rocks of the vent. Above the 1,000-foot level the vein has an average strike of N60°W. In the lower levels of the mine the strike of the vein approximates N75°W. These changes in dip and strike reflect the inhomogeneous nature of the rocks.

Hanging-wall splits of the 43 vein strike east and dip steeply to the south. They join the 43 vein in depth and to the west. Footwall veins dip to the north and join the 43 vein to the east. The tensional nature and attitudes of the foot- and hanging-wall splits indicate that the 43 vein occupies a fracture the side of which has moved westwards and downwards.

Enargite and pyrite are the dominant minerals in this vein system. Galena, sphalerite, and tetrahedrite-tennantite are minor sulfide minerals. In the upper levels of the mine a number of veins in the footwall of the 43 vein are mined in their upper portions for galena and in their downward extensions for enargite.

Northern Vein System

Several large veins notably the 28, 101, 79 and 61 veins, at the northern end of the mine dip steeply south towards the Central Vein System.

The 28 and 101 veins, which are almost wholly in the volcanics, strike towards the northern end of the Pyrite Body. The veins split up in the Pyrite Body and do not pass into the limestone. The strike of the two veins varies from N75°W through E-W to N65°E. The dip of the veins is 70°–80°S.

Enargite is the ore mineral; small amounts of galena and sphalerite occur. In the Pyrite Body where the veins split up into innumerable mineralized fractures, copper orebodies are formed. Galena and sphalerite are in copper orebodies near the pyrite-limestone contact.

The 79 vein between the surface and 600 foot level strikes N50°E and dips N70°–80°S. Little is known of the mineralogy of the vein.

Southern Vein System

The southern vein system includes veins in the Pyrite Body and veins in the Excelsior Formation.

Veins in the Pyrite Body.—Veins in the southern end of the Pyrite Body are along tension fractures, which strike N70°W and dip vertical, 80°S, or 80°N. The principal veins are the 179 vein, the 59B vein and its numerous splits, the 56 vein, and the 207 vein. This group of veins is in the hanging-wall of the San Anselmo vein, which is partly in the Pyrite Body and partly in the Excelsior Formation. The veins split up to the west in the Pyrite Body near its contact with the Lourdes Fragmental.

The San Anselmo vein strikes N60°E and dips 60°N. The vein loses its identity to the east in incompetent black phyllites of the Excelsior Formation. Along its strike to the southwest it probably joins the Excelsior Vein System. The dip of the vein may be largely controlled by the contact of the Pyrite Body with the sediments, which dips about 60°N.

The veins in the Pyrite Body are enargite bearing. Silver is present in argentiferous tennantite. The veins of the system are noted for the rich copper orebodies with which they are associated.

Veins in the Excelsior Formation.—The veins in the Excelsior Formation comprise one large system with a strike length of 3,100 feet. The system, known as the Excelsior-Cleopatra Vein System, is in thin-bedded quartzites that were silicified prior to ore-deposition (3).

The system is approximately parallel in strike and dip to the southern margin of the volcanic vent. The veins forming the eastern end of the system swing to the south away from the contact and split up laterally and vertically where they pass from competent quartzites into less competent shales and phyllites. The strike of the veins ranges from N60°–70°E through E-W to S80°W. The veins have an average 60°N dip.

The strike of the Cleopatra vein varies in much the same manner as the 43 vein. Above the 1,000-foot level a segment of the vein near its eastern

extremity strikes N55°W approximately parallel to the change in strike of the quartzites, which are folded in the form of a northerly plunging anticline.

The Cleopatra vein occupies a normal fault. As the vein splits up to the east it forms an incomplete cymoid loop probably due to the change from competent quartzites to incompetent black phyllites.

The mineralogy of the veins is distinguished by the presence of gold in amounts far greater than found in other parts of the mine. Chalcopyrite and luzonite, coarse pyrite, and quartz are more common than in other vein systems.

Matagente Vein System

The Matagente lead-zinc veins, which are in Pucara Limestone to the east of the northern vein system, probably were developed at the same time as the other veins.

The principal lead-zinc veins at Matagente (1) strike N50°–60°W and dip 70°–80°S. Less economically important veins strike N30°–40°E and dip N80°E. The largest veins in the system are parallel in strike to the first order left-lateral wrench faults and to the main vein of the Central Vein System in the Cerro de Pasco Mine.

Formation of the Vein Systems

A completely satisfactory explanation of the manner in which the veins were formed is difficult to present as insufficient data are available concerning the direction and amount of displacement on the fractures now occupied by veins.

The structural characteristics of the principal veins are shown in Table 2.

TABLE 2

ATTITUDES OF THE PRINCIPAL VEINS

Vein system	Veins	Strike	Dip
Northern	28 & 101	N70°–80°W E–W, N70°E	75°–80°S
	79 6709	N55°E N37°W	75°–80°S
Central	43 & 44	N60°W	65°N
Southern (a) in the pyrite body	56 & 59B	N70°W	80°S
	San Anselmo	N60°E	60°N
(b) in the excelsior formation	Excelsior	N60°–70°E E–W, N80°W	60°N
	Cleopatra	N55°W	60°NE

Generalized grouping of veins according to strike

Easterly and westerly veins:	N70°–80°W, N60°–70°E, E–W.
Northwesterly veins:	N55°–60°W
North-northwesterly veins: (exceptional)	N37°W.

The 28, 101 and Excelsior veins are not parallel (Fig. 4) but they have a marked similarity in their pattern of changes in strike.

In considering the formation of the vein systems allowances should be made for the anisotropism of rocks. More than eight different rock types were involved in the fracturing: namely Rumillana Agglomerate, Cerro Quartz Monzonite, Lourdes Fragmental, the Pyrite Body, Pucara limestone and the slates, phyllites and quartzites of the Excelsior Formation. Each rock type probably reacted in a different manner to compression and thus caused changes in dip and strike of fractures, which would not develop if the area were homogeneous. The already-mentioned change in the dip and strike of the 43 vein is a good example of the effect of different rock types on the structural characteristics of a vein.

The 43 vein, the Matagente veins and the Cleopatra vein are parallel in strike to the N45°–65°W wrench faults. Viewed in plan without reference to the dip the vein systems fit into the pattern of wrench fault tectonics. Probably some normal fault movement took place along the wrench faults when the crossfolds were formed.

Despite the lack of satisfactory evidence the veins are thought to belong to one period of deformation because:

1. The vein systems in the Pyrite Body to the north of the 43 vein split up to the east and those to the south in the Pyrite Body split up to the west.
2. The veins of the northern system join the 43 vein westwards and downwards and the veins to the south join the 43 vein (if projected) eastwards and upwards.
3. The 43 vein occupies a more or less central position with respect to the northern and southern vein systems.
4. The veins were probably developed at the same time as the wrench faults if doming in the Cerro de Pasco area is due to wrench faulting, and if allowance is made for the inhomogeneous nature of the rocks as a cause of changes in dip and strike.
5. The difference in mineralogy may be due to the type of wall rocks involved (4) and not to different periods of mineralization.

The distribution of the veins has a direct bearing on the location of primary copper orebodies. The narrow parts of the Pyrite Body were less competent than the wide parts during compression. Thus numerous fractures, later mineralized, were developed in areas of relative incompetence; generally at the extremities of the Pyrite Body, which are the home of the greatest number of primary copper orebodies.

COPPER OREBODIES

The copper orebodies, more than fifty in number, range from steeply-dipping cylindrical or ellipsoidal pipes to flat-lying tabular bodies situated in the Pyrite Body between the surface and the 2,700-foot level.

The strike, dip and plunge of the orebodies are influenced by the attitude of the Pyrite Body, lenses of unreplaced sediments, and the distribution of veins and fractures.

The orebodies vary greatly in size. The largest orebodies extend downwards for 600 feet as irregular pipe-like shoots attaining widths of over 200 feet. Orebodies at the lower extremity of the Pyrite Body are developed more in a lateral than vertical direction.

The limits of the ore can be determined only by detailed geological mapping and frequent sampling. The mineralization of the orebodies permits their classification into hypogene and supergene.

Mineralogy

The mineralogy of the copper orebodies is simple. Enargite and chalcocite are the ore minerals and pyrite is th principal gangue mineral.

Supergene Minerals.—Chalcocite is the principal copper mineral in the zone of secondary enrichment. It has been found around the borders of lead-zinc orebodies pseudomorphous after galena and sphalerite. Chalcocite replaces enargite and pyrite on the margins of some primary copper orebodies.

Covellite, malachite, and native copper are minor minerals. The pyrite associated with supergene orebodies is porous and friable.

Hypogene Minerals.—Enargite is the principal and in many places the only constituent other than pyrite of many primary copper orebodies. Numerous closely-spaced veins and veinlets have permitted the dissemination of enargite in the Pyrite Body. Enargite has been found as small inclusions in pyrite and chert and as large massive bladed crystals nearly eight inches long in cavities in the pyrite. It is replaced by or intergrown with tennantite, chalcopyrite, primary and secondary chalcocite, and pyrite, which it also replaces. Enargite predominantly occurs as an open-space filling throughout the mine. The variety of enargite known as luzonite, which differs only in color from enargite, is in the Cleopatra vein and in orebodies with a high gold content.

The silver content of the copper orebodies is attributed to argentiferous tennantite (freibergite). Considerable variations in the silver content of the copper ore exists. Ratios of over 100 ounces of silver to one per cent of copper are common in many silver-bismuth-copper orebodies.

Under the microscope small blebs of chalcopyrite have been observed. In one large orebody, the 12214 orebody, chalcopyrite replaces hypogene quartz and tennantite. It is replaced by bornite and chalcocite. A reaction rim of chalcopyrite separates bornite from quartz.

Large masses of steely gray chalcocite of hydrothermal origin are in the 12214 orebody. Hypogene chalcocite has been reported also from an orebody on the 2,500-foot level. Chalcocite replaces chalcopyrite, bornite, and quartz. It forms mutual boundaries and exsolution grating textures with bornite. It cuts across hypogene quartz and replaces chalcopyrite occupying the core of the quartz crystals.

Bornite apart from its exsolution association with chalcocite, borders quartz and is grouped around clusters of quartz grains.

It was observed that enargite gave way to chalcopyrite-bearing chalcocite. This, together with the microscopic evidence that the sequence of mineraliza-

tion is tennantite-chalcopyrite-bornite-chalcocite, conforms with Lindgren's paragenetic sequence (10).

Bismuthinite has been reported from different parts of copper orebodies.

Black, white, and red chert is the predominant form in which silica occurs. The syngenetic origin of some of the chert has been mentioned previously. Much of the red chert in the orebodies is probably of hydrothermal origin. The white and black chert in most places seems to represent remnants of altered sediments.

Barite has been observed in nearly all of the primary copper orebodies, both in narrow veins and in the copper orebodies north of the 43 vein. The barite is hypogene.

White unctuous material, aptly termed "cold-cream," fills many fractures and vugs near the limits of some orebodies. F. de las Casas (personal communication) found that the "cold-cream" argillic products are varieties of the montmorillonite-halloysite group.

Supergene Copper Orebodies

About twenty copper orebodies have been discovered between the surface and the 600-foot level of the mine. They are mainly small rich shoots of ore above or adjacent to lead-zinc orebodies irregularly spaced over a horizontal distance of 4,000 feet. Their uneven spacing is a result of the differential oxidation of the Pyrite Body and the surrounding rocks.

Controls Affecting Localization.—Controls are chemical, lithological, and structural.

The chemical control is the presence of galena and sphalerite, which precipitated copper from downward percolating ground waters to form chalcocite.

The breccia and "microbreccia" border-zones of lead-zinc orebodies are favorable locii for secondary chalcocite enrichment. In general the pyrite around the lead-zinc orebodies is soft, porous, and friable. Thus the pyrite is sponge-like and allows the passage of groundwaters.

Adjacent to many of the lead-zinc orebodies fractured layers of altered but unreplaced limestone have been hosts to secondary copper orebodies.

The structural controls are:

1. The presence of numerous fractures and channel-ways that allowed the penetration of copper-bearing groundwaters into the zone of primary sulfides.
2. The presence of favorable traps provided by the attitude of the contact of the Pyrite Body with the country rock or bands of unreplaced sediments within the Pyrite Body.

Warps in the contact provided the best traps for secondary copper ore. For example, the A-137 and Noruega orebodies (Fig. 9) are controlled by the changing strikes and dip of the contact of the Pyrite Body with the country rock.

The 621 orebody (Fig. 10) was formed by the interplay of chemical, lith-

ological, and structural controls.[2] The ore is in a band of brecciated and silicified limestones underlying a lead-zinc orebody in the Pyrite Body. The altered limestone is in an asymmetrical north-plunging syncline in the Pyrite Body. Brecciation is most intense where the dip of the altered limestone

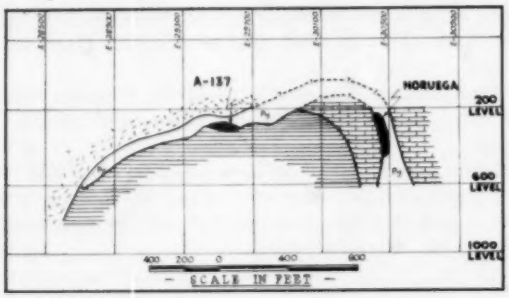

FIG. 9. Section through Mine Co-ordinate N29700 showing the position of the A-137 and Noruega orebodies.

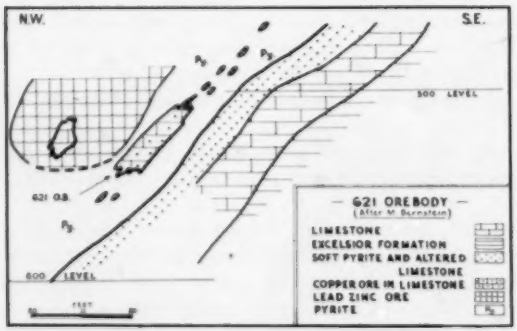

FIG. 10. Cross-section through 621 Orebody showing relationship of the secondary copper ore to relict limestone. Line of section, N25°W through E29632, N30704.

flattens. High-grade ore terminates against less brecciated and silicified limestone. Secondary chalcocite has cemented the breccia.

Hypogene Copper Orebodies

Types.—Primary copper orebodies are of three basic types, namely:

1. "Horsetail" and disseminated.
2. Bolsonada.
3. Combination of 1 and 2.

[2] M. Bernstein, personal communication.

The "horsetail" and disseminated type is found in the northern part of the mine where the veins break up eastwards in the Pyrite Body. These orebodies consist of numerous small veinlets and disseminations of enargite in pyrite.

The bolsonada type of orebody is in the southwestern tip of the Pyrite Body (associated with the 59B and 56 vein systems) where the veins split up to the west at the contact of the Pyrite Body with the Lourdes Fragmental. The ore is in veins, numerous veinlets, in rich pockets (bolsonadas), and vugs.

In the lower levels of the mine a combination of the two types has been reported. Enargite occurs as disseminations in the pyrite near the eastern contact of the Pyrite Body with altered volcanics, as isolated disseminations in massive pyrite, and along criss-crossing flat fractures in the Pyrite Body. The enargite is more coarsely crystalline in the fractures than elsewhere. The pyrite containing the disseminated enargite is thoroughly fractured.

Controls Affecting Localization.—The formation of the primary copper orebodies was controlled by a combination of the following conditions:

1. The width of the Pyrite Body.
2. Changes in strike and dip of the boundaries of the Pyrite Body.
3. "Horsetailing" and intersection of veins.

The changing width of the Pyrite Body and the attitude of its contact with the country rocks were responsible for the splitting of the veins and consequently for the localization of ore within the Pyrite Body.

The veins at the northern end of the mine branch upwards and eastwards away from the 43 vein into the narrow northern end of the Pyrite Body. South of the 43 vein are veins that branch downwards and westwards.

The Pyrite Body, especially those parts made up of "hard pyrite," fractured more readily than the surrounding rocks. The Pyrite Body was less able to withstand compressive stresses at its extremities than at its wide central part. Thus veins are numerous in the narrow parts of the Pyrite Body and poorly developed in its thick central portion.

The changing attitude of the pyrite mass caused inequalities in resistance to stress within the body as a whole. Veins split up as they approach the contact of the Pyrite Body with the country rocks and near "horses" and embayments of unreplaced volcanic and sedimentary rocks. The veins, once they split up rarely continue into the country rocks. Included rocks reduced the homogeneity of the Pyrite Body by leaving comparatively brittle pyrite adjacent to more resistant rocks.

CONCLUSIONS

The nature of the sedimentary rocks and the structures therein prior to replacement controlled the form of the Pyrite Body and its contained orebodies. Lenses of unreplaced and altered sediments played their part in the localization of copper orebodies by reducing the width of the Pyrite Body and hence its competency. Numerous fractures that developed in the less competent parts of the Pyrite Body were later mineralized and permitted dis-

seminations of copper sulfides to such an extent that distinct pipe-like orebodies were formed.

The vein systems may belong to the period of structural activity in late Tertiary times when wrench faults cut through the Cerro de Pasco-Atacocha district.

COMO, WESTERN AUSTRALIA,
May 8, 1960

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LATE PLEISTOCENE AND RECENT ACCUMULATION OF URANIUM IN GROUND WATER SATURATED SANDSTONE DEPOSITS[1]

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ABSTRACT

Protactinium-231 and thorium-230 relations in several ground water saturated sandstones containing uranium ore indicate that much of the uranium has been accumulating in very recent times. Samples from the Hauber mine, Crook County, Wyoming, were selected to illustrate the concept of recent accumulation and the methods of calculation of the estimated minimum and maximum dates of the start of the uranium accumulation. The radiochemical results of eight samples from this mine show extremely consistent radioactive daughter product distribution, and a close correlation between the estimated dates of the start of uranium accumulation and the uranium content of the ore. The results for mill pulp samples, representing large tonnages of ore, indicate that the major part of uranium deposition started between 40,000 and 130,000 years ago and the rate of deposition has increased approaching the present time.

INTRODUCTION

THE results of radiochemical analyses for radioactive disequilibrium on several hundred samples from a wide variety of sandstone type ore deposits indicate that the uranium may be relatively young in many of these samples (7, 8, and unpublished results). Usually a complicated late geochemical history can be expected in most of the deposits because of the generally inconsistent uranium and daughter product relation exhibited. The analyses of ore from the Hauber mine stand out because of their internal

[1] Publication authorized by the Director, U. S. Geological Survey, Contribution No. 285 from The Marine Laboratory, University of Miami.

consistency. The fact that these samples, representing a large tonnage of uranium ore, show a very consistent relation between uranium, protactinium-231, thorium-230, and radium-226 indicates that the ore has undergone a simpler geochemical history than most sandstone type deposits. In this study of radioactive daughter product distribution, designed to use natural tracers for the trail left behind during the migration of uranium, the deposit shows the greatest probability of representing a single generation of uranium mineralization in relatively recent time. Thus, the deposit is selected over many others to illustrate a concept of recent and present-day uranium accumulation that is indicated by protactinium-231 to thorium-230 relationships in several ground water saturated sandstone deposits. Woodmansee (9) has described most of these deposits in conjunction with his ground water studies. A method of calculating the apparent minimum and maximum dates of accumulation is also introduced to present the radiochemical data in a more descriptive form. The term, uranium accumulation, is used in place of the usual term, deposition, because the isotope relationships indicate that the uranium has been undergoing a gradual rate of accumulation in the sandstone for a length of time defined by the minimum and maximum dates as one boundary and the present time as the other boundary.

GEOLOGIC DESCRIPTION

The Hauber mine, the largest uranium mine in the northern Black Hills, is in the Hulett Creek mining area in northwestern Crook County, Wyoming. The Hulett Creek mining area is an area of about two square miles (5). It is east of the Black Hills monocline, which is defined as the western edge of the Black Hills uplift and the eastern edge of the Powder River basin. Uranium deposits occur in the Fall River and Lakota formations of Early Cretaceous age. The ore of the Hauber mine is in a sandstone unit at or near the base of the Lakota formation about 350 to 400 feet below the topographic surface and 250 feet or more below the permanent water table. The basal unit consists of a series of sandstone lenses, from less than 2 feet to 30 feet thick, and interbedded claystone lenses. The sandstone is poorly sorted and the grain size ranges from clay to conglomeratic pebbles up to 2 inches in diameter. Carbonaceous material and carbonate cemented sandstone are locally abundant in the sandstone lenses.

Dips along the Black Hills monocline range from 10° to 25° W. Within the Hulett Creek area, which forms a terrace on the upper side of the monocline, the dips are, in general, 2° to 5° N and NW, with local reversals of 1° to 2°. A series of normal faults ranging in length from less than 100 feet to 5,000 feet cut northeastward from the Black Hills monocline across the Hulett area. The faults strike N 45° to 60° E and dip 50° to 90° NW or SE. Along most of the faults the northwest side is downthrown; the stratigraphic throws ranging from less than a foot to 50 feet. The ore deposit of the Hauber mine occurs on either side of one of these faults. This fault has an average strike of N 50° E and near its middle dips 65° NW with the northwest side downdropped about 30 feet.

The mineralogy of the mine has not been determined as the mine had not been developed when geologic investigations were conducted in the area. However, it is assumed that the uranium minerals are similar to the other disseminated occurrences in the so-called black ores of the Colorado Plateau with low vanadium content (2).

RADIOCHEMICAL ANALYSES AND AGE CALCULATIONS

The radioactive daughter products, protactinium-231, thorium-230, radium-226, radon-222, and lead-210, were determined in all the samples by radiochemical methods (6). Table 1 lists the description of each of the

TABLE 1

MEGASCOPIC AND WEIGHT DESCRIPTIONS OF ANALYZED SAMPLES FROM THE HAUBER MINE

Samples 1–4 are chip samples through the ore zone on the right wall of no. 1. S. drift, 265 ft from shaft.

Sample number	Location	Description
1	Top 2 feet	Sandstone, light-gray streaked with dark-gray, fine- to medium-grained with interstitial clay and sandy clay balls to 2 mm in diameter, friable except for dark-gray streaks, which are cemented with black opaque material.
2	Next 3.5 feet	Sandstone, dark-gray with patches and streaks of light-gray, fine- to medium-grained with interstitial clay, <1–10 mm long slivers of carbonized wood. Gray color results from black coating on sand grains and patches of sand cemented by black material.
3	Next 3 feet	Sandstone, gray to dark-gray, fine- to medium-fine grained with interstitial clay and clay balls of about 1 mm or less, slivers of carbonaceous material <1–5 mm long disseminated in sandstone and concentrated parallel to lamination, friable except for patches and streaks partly cemented with black material.
4	Selected sample 1 foot above base of sample 3	Sandstone, gray to dark-gray, fine- to medium-grained with interstitial clay, 20 percent sandy clay balls up to 5 mm in diameter, carbonized wood fragments from <1–20 mm long, seams of carbonaceous material resembling coal up to 5 mm thick and 75 mm long, irregular pyrite cemented spots up to 10 mm in diameter, streaks <1–5 mm wide of clayey sandstone and carbonized wood cemented with black material.

Samples 5–8 are mill pulp samples from the Hauber mine furnished by the U. S. Atomic Energy Commission.

Sample number	Lot number	Weight (dry tons)
5	188	52.345
6	189	54.830
7	190–191	107.750
8	192–193	106.518

eight Hauber mine samples and Table 2 shows the analytical results. All the daughter isotopes are reported in units of percent equivalent as defined by Rosholt (6). In all the subsequent calculations these units are used.

Further calculations are made on the radiochemical results to obtain estimations of the minimum and maximum dates for the start of the uranium accumulation. The theoretical considerations involved in obtaining these dates are based on the primary assumption that protactinium and thorium will not migrate a significant distance away from where they were generated. The assumption is based on the chemical properties of these elements, which are reviewed by Katz and Seaborg (4); all investigators appear to be in

agreement regarding the extreme tendency of protactinium (V) and thorium (IV) to undergo hydrolysis. The products of the hydrolytic reactions are not well understood, however, the formation first of polymeric ionic species and ultimately colloidal particles or insoluble hydroxides tends to render the two elements quite immobile in natural geochemical processes in sedimentary rock. The basic equations for the growth of radioactive daughter products are shown by Friedlander and Kennedy (1). The specific equations for the growth of protactinium-231 and thorium-230 from the parent uranium isotopes are:

$$Th^{230} = U(1 - e^{-\lambda_{Th^{230}} t}) \tag{1}$$

$$Pa^{231} = U(1 - e^{-\lambda_{Pa^{231}} t}) \tag{2}$$

where λ is the decay constant for the particular nuclide.

Minimum Date.—A minimum date for the start of uranium accumulation would be obtained if the assumption is made that the increase in uranium deposition in the host sandstone proceeds from very low amounts at time, t, to relatively large amounts approaching time zero (present). Thus the greatest fraction of protactinium-231 and thorium-230 would be produced in very recent times. As time, t, approaches zero the term $1 - e^{-\lambda_{Pa^{231}} t}$, will equal $\lambda_{Pa^{231}} t$ and $1 - e^{-\lambda_{Th^{230}} t}$ will equal $\lambda_{Th^{230}} t$. Thus the ratio of total protactinium-231, Pa_T^{231}, to total thorium-230, Th_T^{230}, produced will approach a constant production ratio that is independent of the total amount of uranium atoms disintegrating to produce the two isotopes. The production ratio will be:

$$\frac{Pa_T^{231}}{Th_T^{230}} = \frac{\lambda_{Pa^{231}}}{\lambda_{Th^{230}}} = 2.33. \tag{3}$$

In all the Hauber mine samples the equivalent protactinium-231 content is always greater than the uranium content. This anomaly indicates that a significant amount of uranium has passed through the sandstone, and only a relatively small amount of it has been fixed in the sandstone deposit. All the protactinium-231 and thorium-230 that has been produced from the radioactive disintegration of both the fixed and migratory uranium has been retained in the sandstone where it will decay with 34,300 year and 80,000 year half-lives, respectively. Immediately after production the two isotopes will decay exponentially, with the function $e^{-\lambda t}$ (1), and the following minimum time relationship can be calculated, based on the actual isotope abundances, Pa_A^{231}, and Th_A^{230}, in the sample:

$$Pa_A^{231} \geq Pa_T^{231}(e^{-\lambda_{Pa^{231}} t}) \tag{4}$$

$$Th_A^{230} \geq Th_T^{230}(e^{-\lambda_{Th^{230}} t}) \tag{5}$$

combining equations (4) and (5) with equation (3) together with the logarithmic elimination of the exponential terms gives:

$$(\lambda_{Pa^{231}} - \lambda_{Th^{230}})t = \ln(\lambda_{Pa^{231}}/\lambda_{Th^{230}}) - \ln(Pa_A^{231}/Th_A^{230}) \tag{6}$$

and

$$t_{min} \geq [0.845 - \ln (Pa_A^{231}/Th_A^{230})][0.866 \times 10^5 \text{ years}]. \quad (7)$$

Maximum Date.—A maximum date for the start of the accumulation of uranium would be obtained if the assumption is made that uranium deposition proceeds from relatively large amounts at time, t, to very small amounts approaching time zero (present).

Thus the initial uranium deposited in the sample at time, t, would be retained until very recent times (assumed at $t = 0$) when a major portion of the uranium was leached out. During this time protactinium-231 and thorium-230 were produced from the decay of the original uranium present according to the growth functions given in equations (1) and (2). The

TABLE 2

CHEMICAL AND RADIOCHEMICAL ANALYSES OF SAMPLES FROM THE HAUBER MINE

Sample number	USGS serial number	Percent		Percent equivalent					Percent					PPM		
		eU	U	Pa^{231}	Th^{230}	Ra^{226}	Rn^{222}	Pb^{210}	V_2O_5	Total Fe as Fe_2O_3	CaO	MgO	CO_2	Mn	As	Se
1	269010	0.046	0.048	0.077	0.043	0.060	0.05	0.050	0.44	0.18	0.21	0.13	0.26	72	11	0.5
2	269011	.29	.33	.37	.27	.40	.28	.32	1.81	.59	.78	.51	.91	148	90	50
3	269012	.53	.56	.79	.54	.69	.48	.57	1.01	.46	1.47	.22	.98	76	37	9
4	269013	1.1	1.30	1.50	1.24	1.22	1.0	1.08	.19	.17	2.38	.23	1.12	72	16	8
5	271915	.15	.17	.24	.15	.17	.14	.15	.3	2.8	4.22	1.5	4.21	500	65	40
6	271916	.16	.19	.25	.17	.18	.15	.17	.3	2.0	4.10	1.5	4.11	700	65	35
7	271917	.14	.16	.24	.14	.16	.13	.14	.3	3.4	4.43	1.5	4.44	700	65	50
8	271918	.15	.17	.25	.18	.18	.12	.15	.3	2.2	4.31	1.7	4.22	800	65	50

Analysts: eU, L. M. Lee; U, H. H. Lipp; Radiochemical, J. N. Rosholt; V_2O_5, Fe, Mn, W. D. Goss; CaO, MgO, W. Mountjoy and E. J. Fennelly; CO_2, I. C. Frost; As, C. Huffman and D. L. Ferguson; Se, G. T. Burrow.

maximum time relationships for the ratio of the actual abundances in the sample would be:

$$Th_A^{230}/Pa_A^{231} = (1 - e^{-\lambda_{Th^{230}}t})/(1 - e^{-\lambda_{Pa^{231}}t}) \quad (8)$$

Since the above equation cannot be solved directly for t, as a simple function of Th_A^{230}/Pa_A^{231}, an empirical equation which gives values very near the correct values for t up to 250,000 years can be shown to be:

$$t_{max} = [(Th_A^{230}/Pa_A^{231})^2 - 0.18]3.9 \times 10^5 \text{ years}. \quad (9)$$

Thus the actual time required for the accumulation of the uranium should be from a point in time between the two values of t calculated from equations (7) and (9) and the present.

Figure 1 shows the comparison of the minimum and maximum dates plotted against the theoretical relative rate of accumulation for each sample. That is, the uranium at the minimum date would proceed from a low rate of accumulation at time, t_{min}, to a relatively high rate at time zero; whereas the

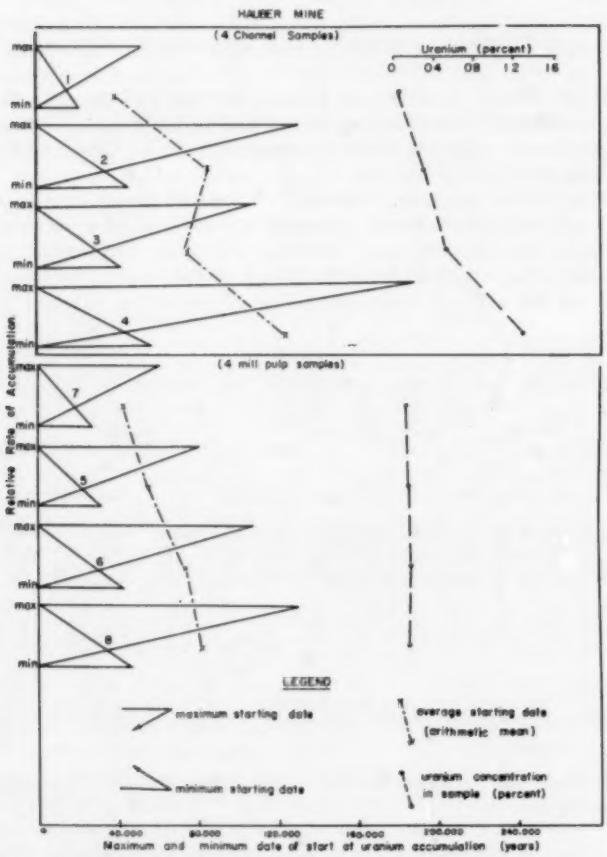

FIG. 1. Minimum and maximum dates of start of uranium accumulation.

uranium at the maximum date would proceed from a relatively high rate of accumulation at time, t_{max}, to a very low rate at time zero. The comparison of the uranium content of each sample with the average date of the start of uranium accumulation is also shown on Figure 1.

INTERPRETATIONS OF THE MIGRATION OF URANIUM

The most obvious interpretation arises from the close correlation of increasing uranium content with increasing age. The conclusion that uranium is still accumulating in this deposit at the present time is primarily based on this positive correlation. The differences between the uranium content and the abundances of protactinium-231 and thorium-230 indicate

that the efficiency of uranium accumulation is relatively low. Thus, only a small amount of the total uranium available is permanently fixed in the sandstone, while a large portion of the uranium associated with the sandstone has subsequently been removed. It is very probable that the source of the uranium is ground water supply by multiple migration accretion as proposed by Gruner (3). In spite of the low efficiency of fixation of the uranium, the age results on this deposit indicate that very substantial quantities of uranium can be extracted from ground water in relatively short periods of time. Variations in ground water flow and position between the present time and the glacial and interglacial environments during the last 130,000 years would have considerable effect on the rates of uranium accumulation and the potential supply of uranium leached from above. In this particular location, a source of uranium is available from the deposits in the overlying Fall River formation. In collaboration with the geologists who have investigated the Hulett Creek area, a report on the migration of uranium in the Fall River formation is being prepared. Further evaluation of the effect of the Fall River deposits on the Hauber mine ore may be possible.

A broader conclusion regarding the geochemistry of uranium under ground water control in permeable sandstones may give a clue as to the unstable nature of uranium under these conditions. As long as conditions are favorable for uranium fixation in the sandstone, the uranium content will increase in that particular locality. As soon as these conditions are removed then the uranium concentration thus produced will become a disintegrating deposit and will continually deplete its concentration with subsequent contamination of the host sandstone as it is moving out.

ACKNOWLEDGMENTS

This report concerns work done on behalf of the Division of Raw Materials, U. S. Atomic Energy Commission. The author is indebted to C. S. Robinson, Geologist, U. S. Geological Survey, for supplying the description of the geology of the Hauber mine along with the samples analyzed from that mine, and the National Science Foundation for their support.

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SCIENTIFIC COMMUNICATIONS

A MAGNETITE "FLOW" IN NORTHERN CHILE

CHARLES F. PARK, JR.

This short note is written as the result of a recent trip into the Laco area of the highlands of northern Chile to examine reported iron ore deposits. The area lies at an altitude of about 15,000 feet, and is about 180 miles from the coast at Antofagasta (Fig. 1).

The Laco area has been visited by several geologists since the iron ore was first reported in 1958. A small amount of trenching and tunneling has been done, but almost nothing is available concerning the nature of the deposits below the surface. Because of their unusual physical characteristics, the deposits have excited a great deal of comment and discussion. The ores

FIG. 1. Index map of the Province of Antofagasta, showing the location of Laco.

are principally magnetite and hematite, the only impurities are tiny needles of apatite and a few small blebs and patches of silica. Four areas of outcrop of the oxides are known within an airline distance of about three kilometers. These outcrops are on the side of a range of mountains that contains several active volcanoes, and that appears to be made up entirely of volcanic materials. Many of the rocks are of recent age, and probably most are no older than Tertiary. The most common material near the magnetite-hematite seems to be a light colored tuff, probably near dacite in composition, though no microscopic study of it has been made. The deposits of magnetite resemble basalt flows, and if they were composed of basalt instead of magnetite, their

FIG. 2. Surface of magnetite-hematite body, Laco Norte.

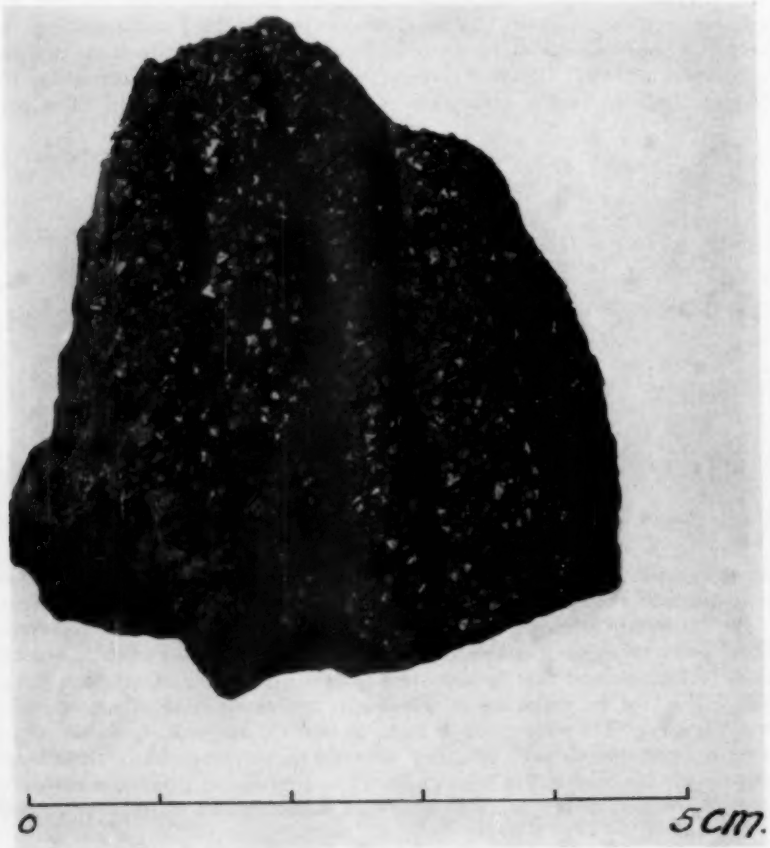

FIG. 3. Ropy surface on fragment of magnetite. From surface at Laco Sur.

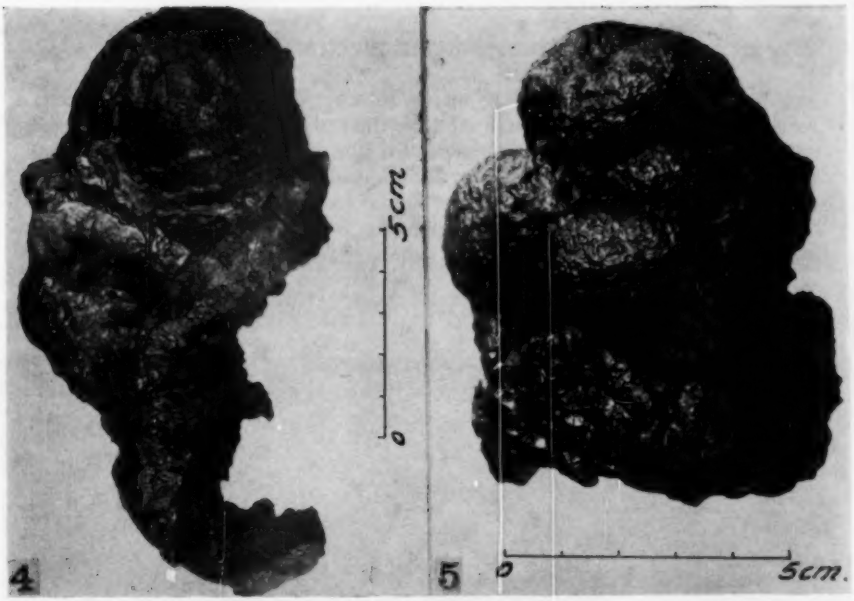

FIG. 4. Blister of magnetite-hematite from the surface at Laco Norte.
FIG. 5. A magnetite-hematite bubble, from the surface at Laco Sur.

FIG. 6. Interior of the same bubble as shown in Fig. 5.

origin as flows would probably go unquestioned. They show so many characteristics of shallow intrusions and flows that they are considered to have solidified from a magma composed almost entirely of iron oxides and abundant gas. This "ore magma" appears to have intruded the tuff at shallow depths, and in places to have broken out and flowed over the surface.

The surfaces of the magnetite-hematite bodies resemble in places the surfaces of aa flows of basalt (Fig. 2), but elsewhere ropy surfaces are more of the pahoehoe type (Fig. 3). The upper surfaces show many large bubbles or blisters of magnetite-hematite (Figs. 4, 5, 6), and many interesting hollow

FIG. 7. Vertical section in the Laco Sur magnetite-hematite deposit, showing gas tubes. The upper surface of the deposit is about 1 m above the hammer.

tubes that are interpreted to be gas escape tubes. In places these tubes extend for at least several meters down into the magnetite-hematite. Figure 7 shows the gas tubes in a vertical section of the magnetite-hematite rock at Laco Sur. In detail the tubes are lined with well-formed magnetite crystals, generally less than 1 cm in longest dimension, though exceptional crystals 5 cm or more in length are found. The bulk of the magnetite around the tubes is fine-grained, and broken sections of the rock show almond-shaped vesicles (Fig. 8). Parts of the walls of the tubes are extremely porous and spongy, with up to nearly fifty percent of voids (Fig. 9).

The contacts between the magnetite-hematite and the tuff are poorly exposed and they yielded no information of interest. The process of replacement, if active at all, is extremely minor, and diligent search revealed only a few small patches where replacement was even suggested. Likewise, no evidence was found that would point to an exhalative origin.

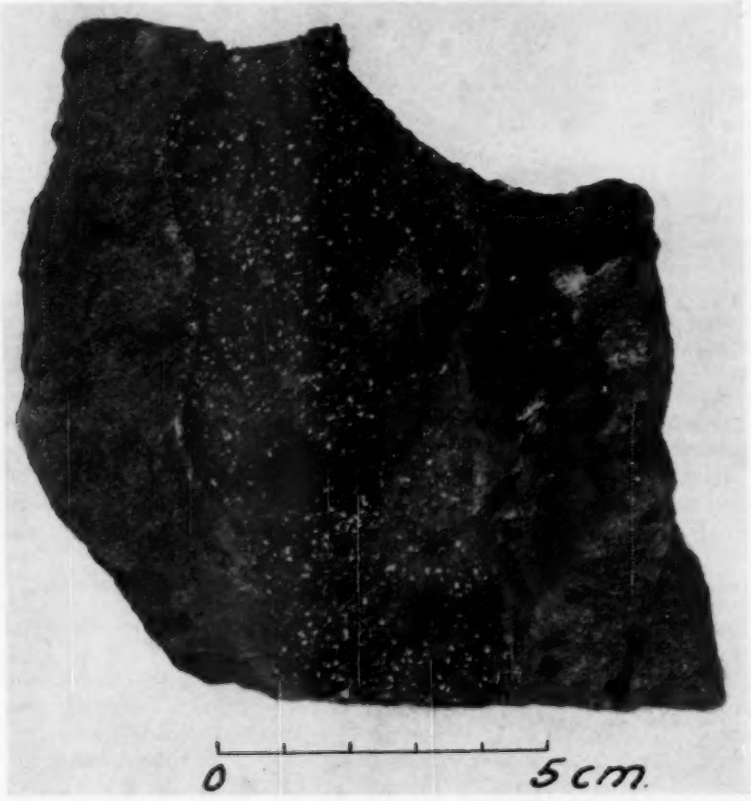

FIG. 8. Photograph of a broken gas tube in magnetite, showing the crystalline character of the lining and the finer-grained magnetite in the walls. Note the vesicles in the lower right hand corner of the specimen.

A more precise statement of the nature and origin of the Laco deposits must await detailed studies and possibly exploration at depth. So far as is known, no flow of magnetite-hematite has ever been described, though magmatic injection deposits of magnetite are widely recognized, and some are thought to have been intruded at comparatively shallow or at moderate depths (1). A flow of magnetite-hematite would appear to be a possibility, provided

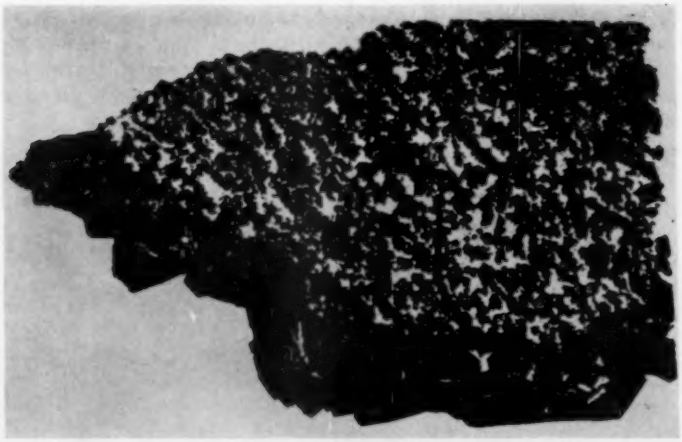

FIG. 9. Photograph of a thin section along the border of a gas tube. Note the large amount of voids in the magnetite. Larger crystals on the edge of the tube suggest recrystallization of magnetite by gases.

its temperature was approximately 1,500° C or more (2). The large amounts of gas indicated by textures and structures may well have lowered the melting temperature appreciably.

The accompanying laboratory photographs were taken by Ruperto Laniz, and his patience and excellent skill are deeply appreciated.

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STANFORD UNIVERSITY,
CALIFORNIA,
Dec. 14, 1960

RADIOACTIVITY IN MONAZITE, ZIRCON, AND "RADIOACTIVE BLACK" GRAINS IN BLACKSANDS OF ROSETTA, EGYPT

AMIN R. GINDY

Because of the contrasting provenances drained by the upper reaches of the Nile, more than 50 different heavy minerals are known to occur in the Egyptian Nile deposits (7). Small scale concentrations of these heavy minerals form on the present beaches of the Nile delta of which the most important occur near the Rosetta mouth of the Nile. The mechanism of

their concentration had already been outlined by Davidson (1) and Rittmann (5). These are ephemeral heavy mineral concentrates constantly changing in composition and place, and since 1939 they have been increasingly excavated for their ilmenite, magnetite, zircon, and monazite content. The Rosetta blacksands are fairly well sorted and contain about 70 to 90 percent by weight of heavy minerals; the average zircon and monazite contents range from 7 to 8, and 0.5 to 1 percent by weight respectively. By means of a variety of techniques with nuclear photographic emulsions (2, 3, 6, and 8), the radioactivity of the different individual grains of monazite, zircon and "radioactive blacks" was investigated from heavy mineral fractions of representative Rosetta samples. In the following, all unspecified radioactivity values are expressed in alphas/cm²/sec.

RADIOACTIVITY OF MONAZITE GRAINS

The pure concentrate of the Rosetta monazite grains has a buff brownish orange color and fluoresces in deep vermillion colors under ultraviolet light. It has a specific gravity of 5.166. A representative pure powdered sample, adequately stored, has a radioactivity of 3.473 corresponding to an approximate equivalent thoria content ($eThO_2$) of 6.52 percent. A chemical analysis of a sample of about 98 percent purity indicated ThO_2 and U_3O_8 contents of 5.80 and 0.44 percent respectively (4). The combined activity of this thoria and urania would correspond to an $eThO_2$ content of 7.20 percent, about 9.44 percent higher than the value deduced by nuclear emulsions.

The bulk (about 85 percent by weight) of the Rosetta Monazite grains falls in the 135–73 microns size ranges. Under the microscope, the majority of the grains has well rounded or oval outlines but some show rectangular-like euhedral outlines, generally with rounded corners. They display weak to appreciable pleochrism from colorless to pale yellow or lemon yellow. The grains are mostly clear with few foreign small inclusions but some are variably altered, with orange to deep red or brown stains, films, dust granules, or opaque patches particularly along irregular fractures and incipient cleavage planes. The individual grains are not equally radioactive (Fig. 1) and the observed surface activity ranged from 1.447 to a maximum of 7.500 corresponding approximately to $eThO_2$ contents from 2.720 to 14.087 percent, assuming all grains to have the same permeability to alpha particles. The different activity values are rather symmetrically distributed around a "median activity" value of 3.23 corresponding to the 50 percent frequency of the cumulated curve. This value is about 7 percent different from the overall activity value of 3.473 obtained from the powdered pure monazite concentrate. Preliminary studies on the correlation of the activity of the monazite grains with their size, shape (sphericity), roundness and degree of alteration suggested the absence of any of these relations. Alpha track counts on different areas on the surface of individual monazite grains did not show substantial differences either, even over clouded and altered parts, suggesting thus a rather homogeneous emission of alpha particles from the surface of each grain.

RADIOACTIVITY OF ZIRCON GRAINS

The pure zircon concentrate from the Rosetta blacksand has a specific gravity of 4.583 and its stored powder has a radioactivity of 0.0452 roughly corresponding to an $eThO_2$ content of 0.1087 percent (or eU_3O_8 content of 0.0341). About 65 and 22 per cent by weight of the Rosetta zircon grains fall in the 105-73 and 135-105 microns size grades respectively. Petrographic examination of the zircons reveals the presence of several species

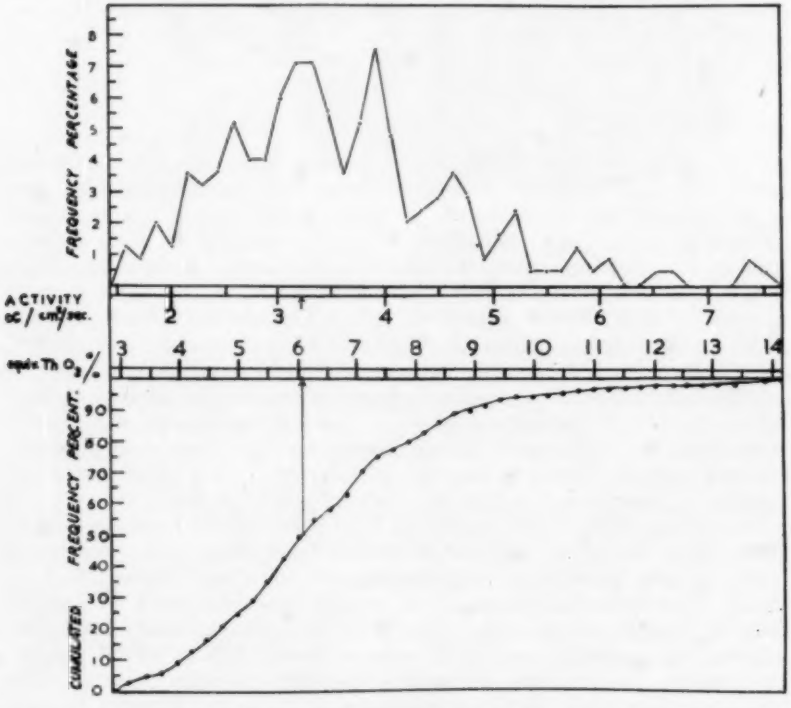

FIG. 1. Frequency distribution of surface radioactivity of 250 random monazite grains from the Rosetta blacksand.

(more than 20) but for a simplified combined radio-petrographic grouping, these may be reduced to seven main groups. Data on the activity and frequency of these groups are summarized in Table 1 and Figure 2. In general, the darker and/or more zoned zircons are more radioactive than colorless unzoned zircons. The distribution of surface activity in the different parts of individual grains is on the whole rather homogeneous though deviations are more common in zircons as compared with monazite grains. The

TABLE I

OBSERVED RADIOACTIVITY VALUES FOR THE DIFFERENT GROUPS OF ZIRCON PRESENT IN THE ROSETTA BLACKSANDS
(Activities in alphas/cm /sec)

Group of zircon	Activity			Approximate percentage frequency
	Minimum	"Median"	Maximum	
I	0.0095	0.0418	0.1856	over 88
II	0.0190	0.0857	0.1280	below 7
III	0.0095	0.0292	0.0999	below 2
IV	0.0523	0.0952	0.2570	below 3
V	0.3617	0.5093	0.8568	
VI	0.0428	0.1523	1.3804	
VII	(0.1428)	(0.0762)	(0.1856)	

commonest and sharpest deviations occur in grains of Group VII. A very brief account of the chief characteristics of each zircon group is given below:

Group I. A flood group of typically euhedral, less commonly stumpy, colorless prismatic crystals with interesting series of inclusions in endless varieties of color, composition, shape and arrangement. Discernible zoning is very rare.

Group II. Grains are typically well rounded and have a relatively darker gray or cream color than the preceding group. They commonly contain inclusions.

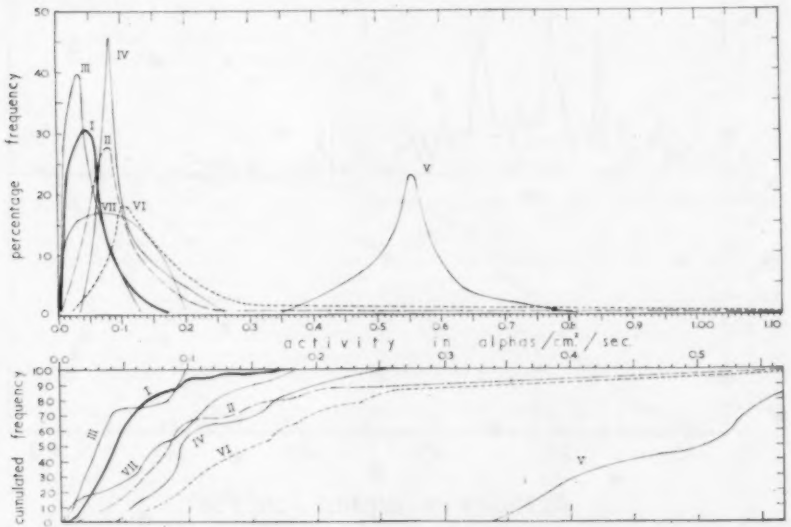

FIG. 2. Frequency distribution of surface radioactivity observed in the different groups of Rosetta zircon grains.

Group III. Grains are typically barrel-shaped, colorless, limpid, without or with very few inclusions.

Group IV. Grains are typically zoned euhedra or subhedra made up almost entirely of delicate laminae. Color grayish, cream, or bronze.

Group V. This is a rare distinct radioactive group distinguishable only by nuclear emulsions. Grains are colorless to pale cream, mostly euhedral to subhedral and rather free of inclusions. A grain made up of a geniculated twin was observed in this group.

Group VI. Several varieties are included in the last four groups in Table 1, all having in common red to brown colors or almost opaque brown as well as black metamict members of the malacon type. Grains may be euhedral to rounded, and there is a wide pattern of color distribution or color zoning inside the grains. Red colors in this group are not actually transparent reds but are due to red dust granules and clots. Some of the most radioactive grains in this group probably belong to xenotime.

Group VII. A mixed batch of very rare clear colored zircons, mostly in yellows and several shades of red (lilac, hyacinth, rosy, mauve, deep red). The color is always a transparent body color not caused by dust inclusions.

RADIOACTIVITY OF "RADIOACTIVE BLACK" GRAINS

These are dark colored or black metamict grains more active than the most radioactive monazite grains. They were discovered in the course of

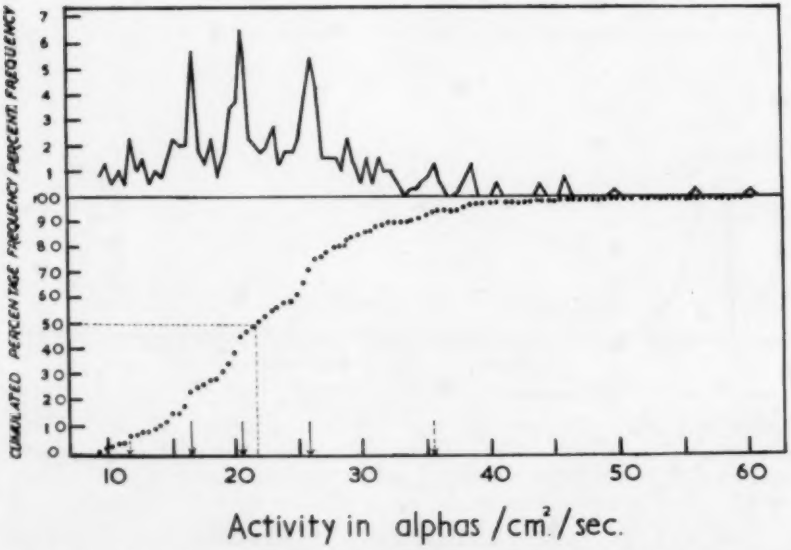

FIG. 3. Frequency distribution of radioactivity observed in 408 Rosetta "radioactive black" mineral grains including those of thorite.

the present study and have not been previously recorded. Data on the radioactivity of some 400 of these grains are summarized in Figure 3. Under strong transmitted light, the majority of these grains becomes translucent in brown and red brown colors, few grains become bluish, greenish or just remain black. Several varieties of thorite grains can be readily identified and preliminary studies on other grains suggest the presence of one or more members of the complex niobates and tantalates of the euxenite-polycrase series, betafite, very rare thorianite, and other "unknowns." Confirmatory diagnosis of the Rosetta "radioactive black" grains by X-ray diffraction and other specialized techniques awaits a future investigation. These "radioactive blacks" tend to be concentrated in the electromagnetic fractions rich in monazite and in the slightly more magnetic ilmenite-garnet rich fractions, the majority in the former. The frequency of these "blacks" in the Rosetta blacksand was roughly determined relative to monazite by simply sprinkling grains lightly from representative heavy mineral grain concentrates on several horizontal nuclear plates that were then gently tapped and left for about 10 to 15 days. The sprinkled grains were then gently removed and the developed plates showed under small magnifications distinct autoradiographs of monazite and "radioactive black" grains readily distinguishable from each other by the relative density of their alpha track populations. Counts of these autoradiographs indicated that the "radioactive black" grains have an average frequency of 0.8 percent of the monazite grains. Since the frequency of monazite grains in the heavy fractions used was about 1 percent, the frequency of the "radioactive blacks" would be below 0.01 percent, probably in the range 0.01–0.007 percent.

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Oct. 25, 1960

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DISCUSSIONS

THE CONSTITUTION OF DAVIDITE

Sir: I was most interested to see the paper on davidite by J. D. Hayton (1) and to compare his results and views with our findings (2). He presents comprehensive analyses for davidite whereas most of our data are confined to the rare earths in davidite. It is good to see that where we have considered minerals from the same locality our data are closely comparable. We differ, however, in our interpretations of the role of the rare earths and associated elements in davidite.

The relevant elements listed in order of decreasing ionic radius in Å units after Ahrens (3) are: Pb^{+2} 1.20, La^{+3} 1.14, Sr^{+2} 1.12, Ce^{+3} 1.07, Pr^{+3} 1.06, Nd^{+3} 1.04, Th^{+4} 1.02, Sm^{+3} 1.00, Ca^{+2} 0.99, Eu^{+2} 0.98, Gd^{+3} 0.97, U^{+4} 0.97, Tb^{+3} 0.93, Dy^{+3} 0.92, Yt^{+3} 0.92, Ho^{+3} 0.91, Er^{+3} 0.89, Tm^{+3} 0.87, Yb^{+3} 0.86, Lu^{+3} 0.85, and Sc^{+3} 0.81. The radius range for the lanthanons, elements with atomic numbers from 57 to 71 inclusive, may be indicated as Ln^{+3} 1.14–0.85 Å. Dr. Hayton considers that Pb^{+2}, U^{+4}, Ln^{+3}, Yt^{+3} Th^{+4}, Sc^{+3}, Ca^{+2} and Sr^{+2} occupy similar structural positions whereas I suggested that La^{+3} and Ce^{+3} (with lesser amounts of Pr^{+3} and Nd^{+3}) occupy unique structural positions different from those occupied by U^{+4}, Yt^{+3}, Dy^{+3}, Er^{+3} and Yb^{+3} (with the lesser amounts of Ho^{+3}, Tm^{+3} and Lu^{+3}). I think that the latter explanation is more favorable in considering the role of Sr and Ca in davidite (from the data given by J. D. H.). SrO varies from 0.05 to 0.6 wt.% and CaO from 0.15 to 0.9 wt.%; the ratio Sr/Ca (at.) varies from 0.12 to 1.6 and averages about 0.5. None of the davidites so far described is associated with nepheline syenites or allied rocks and if Sr^{+2} and Ca^{+2} replace U^{+4} and the lanthanons then the ratio Sr/Ca might be expected to be comparable with those found in other rare earth minerals.

In monazite Asari (4) found Sr/Ca (at.) to vary between 0.05 and 0.02 for eleven Japanese samples. Monazite may be considered as (Ce, La, Nd) PO_4 with other light lanthanons substituting for Ce etc. The size of the principal rare earth is nearer to that of Sr. than Ca. In uraniferous rare earth minerals like euxenite-polycrase, samarskite or yttrotantalite La and Ce contents are invariably low and Yt and the heavier lanthanons predominate. From a consideration of ionic size it might be supposed that Ca^{+2} would be much more readily accommodated than Sr^{+2} in Ln^{+3}, U^{+4} positions. Ionic size is not the only criterion on which to base an expectation of or explanation for substitution even for elements that are exclusively lithophile. It is not

possible to indicate which rare earth or alkaline earth is the "best fit" in positions normally occupied by U^{+4} and Yt^{+3} in metamict minerals. Samarskite, for example, appears to be highly selective towards Gd + Tb + Dy (5, 6), and members of the euxenite-polycrase series have a wide tolerance to rare earth ions of different sizes. In the aeschynite-priorite series rare earth variation is used as a basis for deciding nomenclature—the light lanthanons predominate in aeschynite, the heavy lanthanons and Yt in priorite. But it seems very likely that in aeschynite the appreciable Th content is to be correlated with the light lanthanon content whereas in priorite where U exceeds Th substitution of Yt and the heavy lanthanons is more normal.

Data for Sr/Ca ratios are sparse in all of the uraniferous rare earth minerals mentioned above but values for CaO are fairly abundant. Where CaO exceeds 1%—and this is a frequent occurrence—it is reasonable to assume that the analyst will not have neglected to consider Sr and that Sr when unreported or undetected will be subsidiary to Ca. Thus Sr/Ca ratios might very well be lower than those recorded in monazite except possibly for aeschynite-rich members of the aesychnite-priorite series.

The very marked enrichment of Sr to Ca in davidite is accordingly attributed to these two elements having distinct and separate structural roles in davidite. Sr^{+2} proxies for La^{+3} and Ce^{+3}; Ca^{+2} proxies for Yt^{+3}, U^{+4} and the heavier lanthanons.

A structural formula for davidite would include the groups La, Sr, Ce, Pr, Nd (group P) and Pb, Ca, U, Dy, Yt, Er, Yb (group Q). The ratio of group P to Group Q atoms varies from 0.52 to 1.36 for the davidites analyzed by Dr. Hayton; the average ratio is 0.95.

The structural distinction between group P and group Q elements explains the general paucity of Th in all analyzed davidites. Th^{+4}, with a size of 1.02 Å, is too large to be conveniently accepted into U, Yt etc. positions and too small to be conveniently accepted into La, Ce etc. positions. Moreover, in view of the suggested role of La and the high La/Ce ratio in davidites it is possible that common lead might have been contained in davidites at the time of their formation. The size difference between La^{+3} and Pb^{+2} would embrace this possibility and the relatively high La/Ce ratio suggests that the "best fit" in La positions might be from an ion larger than La (1.14 Å). On the other hand the lower charge of Pb^{+2} might not particularly favor the substitution Pb^{+2} for La^{+3}. No doubt isotopic studies will establish that most of the lead in davidite is radiogenic.

It may be concluded that davidites, in addition to showing a peculiar and diagnostic lanthanon distribution, are chemically characterized by (1) a relatively high Sr/Ca ratio combined with a low alkaline earth content, (2) a relatively high U/Th ratio combined with a low ThO_2 content.

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ORE DEPOSITS AND SEDIMENTARY FEATURES IN TENNESSEE

Sir: The paper by David L. Kendall [1] on the geology of the Jefferson City Mine describes some very interesting features which, if correctly interpreted, must profoundly affect the generally held ideas of origin of these deposits. While the author concludes with an expression of some doubts as to the ability of sedimentary processes to account for all the evidence, he nonetheless casts his vote in that direction as the prime concentrating agent for the zinc mineralization. The following comments are intended as an expression of the opinion that there are some features in the East Tennessee district which do not fit well into a syngenetic hypothesis.

1. The interpretation of the sand filled vugs as evidence of ore deposition prior to tilting is of prime importance as this would rule out any connection with the Appalachian orogeny. Many geologists have felt that this late Paleozoic disturbance gave rise to the structural traps through folding and faulting and that the accompanying igneous activity was the source of the hydrothermal ore solutions that they advocated. Obviously, if the ore deposits are pretilting, this hypothesis is incorrect.

The exact mode of origin of these sand filled vugs is difficult to visualize. How, in a highly irregular opening with no determinable inlet or outlet, is it possible to get relatively coarse, locally derived material laid down in graded beds including fragments of sphalerite? It seems no easier to make them sedimentary than much later, as the work of ground water such as is so abundant in East Tennessee today, or even as a result of action of a hydrothermal solution.

The relative attitude of the sand laminations and the country rock bedding is the significant bit of evidence. Due to the relatively gentle dips in the Jefferson City area, it would appear quite difficult to ascertain positively that parallelism with the bedding did exist in such irregular, ramified sand bodies. If such features could be found in the mine at Mascot, where the dips are 20–40 degrees, the evidence would be still more convincing. This is such an important point that it is to be hoped that other workers in the district will report on their findings.

[1] Kendall, David L., Ore deposits and sedimentary features, Jefferson City Mine, Tennessee: Econ. Geol., vol. 55, p. 985–1003, 1960.

2. The identification of reefs or reef-like bodies in the ore section is especially interesting since reef masses are known in other districts of the Mississippi Valley Type (e.g., Southeast Missouri) where they have a great influence on ore distribution. Apparently in East Tennessee these organic structures are restricted to R, S, and U beds, with the best developments being in U bed, a well mineralized but relatively minor unit tonnagewise near the base of the ore section.

The question that is raised does not dispute the presence of reefs but rather their extent and their importance in the origin of the ore deposits. With the exception of certain relatively restricted, stromatolite-like masses such as those illustrated in Figure 9, this is not obviously reef rock as is the "Fingered rock" in Southeast Missouri. Identifiable structures are the exception rather than the rule. All reef rock is coarse grained but not all coarse grained rock is reef. Distinguishing between the two is not easy but it is questionable whether a very large percentage of the widespread coarse "recrystalline" in the Kingsport is really organic in origin. The region does not have the characteristic rapid facies changes nor the mound-like structures characteristic of reef environments. Instead it is an area of remarkable persistence of minor rock units so that thin, distinctive chert beds or sandy layers can be followed for miles, through ore bodies and through barren country rock between ore bodies. And, instead of these units arching upward upon entering the ore bodies (reefs) as might be expected, the great tendency is for them to sag downward.

This issue is raised as to the distribution and healthy vigor of the East Tennessee algal reefs because, on page 1002, Mr. Kendall has called upon them to precipitate the zinc from the sea water. My contention is that this just doesn't look like an area of big reef development and the zinc deposits are spread too far beyond the structures that can be proved to be organic. In any event, reefs cannot be called upon to explain the great breccia type ore bodies in fine grained dolomite, which have provided such a large share of the district's production.

3. Concentration of zinc by organic action does happen but did it happen in Tennessee? Seventy miles southwest of Jefferson City, at Sweetwater, fluorite and barite are the ore minerals found in a structural and stratigraphic setting much like that at Jefferson City. It would seem imperative for any theory of ore deposition to explain both deposits. Can algae precipitate barite and fluorite?

4. The sedimentary theory does not give a ready explanation for the fact that many East Tennessee ore bodies are associated with arch and dome structures. Kendall indicates (page 988) that within the zinc district "there is folding and doming that is rare in East Tennessee." It certainly is true that warps of the bedding of varying degrees of intensity are associated with most of the hundreds of zinc showings in this mineral province. It would seem more reasonable to theorize that the mineralization was introduced later and found these tectonically prepared areas favorable than that late structural features just happened to be coincident with mineralized sedimentary phenomena in so many places.

This is not to derogate the influence of reefs, facies changes, sedimentary

breccias, etc., as secondary influences on ore distribution. There are too many examples that these have been important just as they seem to be in the U bed ore at Jefferson City, but it seems very unlikely that the primary reason for the location of the East Tennessee district is the presence or absence of such features.

This very interesting paper is a distinct contribution to the literature of the ore deposits of the Mississippi Valley type and it is especially valuable in that it puts in print for the first time descriptions of some of the details of ore occurrence in this major zinc district. Results of similar close observations in other mines in the area would be most welcome, particularly for those mines where the ore is in different stratigraphic horizons. It is believed that evidence from higher beds would tend to point toward an epigenetic origin for the deposits.

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REVIEWS

Geology of Ore Deposits (Geologiya Rudnykh Mestorozhdenii). Academy of Sciences of the USSR. March–April, 1959; Vol. 1, No. 2 (in Russian).[1]

Problems of Study of Metallic and Non-metalic Mineral Deposits During the Coming Seven-year Period (Pp. 3–5).

The problems associated with the development of the country's economy during the period 1959–1965 are outlined with emphasis on increasing the reserves of mineral deposits. The development of new areas requires the elaboration of principles and methods of forecasting the location of new ore fields, preparation of metallogenetic maps (especially in the eastern parts of the country), study of relation of mineralization to intrusives, zoning of mineralization, research on rare and minor metals present in other ores, study of isotopic composition of elements in connection with the problems of ore genesis, formation of zones of weathering and gossans, migration and redeposition of material derived in the zone of weathering, deposition of ores in sedimentary basins, diagenesis of these sediments, and their consecutive alteration. This program reflects the principle of centralization, governmental planning, and control of all branches of industry and science in the Soviet Union.

P. M. Tatarinov, Role of Enclosing Rocks in the Process of Formation of the Endogenetic Mineral Deposits (Pp. 6–16).

After a historical review of the metallogenetic hypotheses and theories developed during the past three centuries, the author discusses the following points of view of Russian geologists relative to the problem of influence of country rocks on the formation of endogenetic ore deposits:

1. The deposition of mineral matter as the result of chemical reaction of ore-bearing solutions with the enclosing rocks is a major factor in distribution of mineralization. K. N. Ozerov analyzed several hundred postmagmatic ore deposits and concluded that most of the economic deposits are located predominantly in rocks consisting of alkaline feldspars or calcium and magnesium carbonates. Acid effusives and their pyroclastics, acid intrusive rocks, arkoses and feldspar quartzites, and the carbonates are favorable rocks for emplacement of ore. Shales, phyllites, basic and ultrabasic rocks are unfavorable for mineralization. Tatarinov agrees with Ozerov, however with a reservation, since the influence of lithology of the enclosing rocks on mineralization cannot be considered separately from other geological phenomena, such as the presence of ore-bearing intrusions, favorable tectonic structures, etc.

2. The influence of country rocks on the form of ore bodies and conditions of their emplacement was analyzed in detail by A. V. Korolev (1951). The basic

[1] Regular preparation of reviews of this journal is supported by a grant from the National Science Foundation.

rock properties determining the form and conditions of emplacement of ore bodies are physical anisotropy, competency, permeability, and chemical activity with respect to solutions. The ore bodies are classified as bodies crossing the bedding planes of strata, ore bodies parallel to the bedding, contact ore bodies, and ore bodies of combined character. Each type of ore body is most characteristic of a particular type of rock. E.g., ore bodies parallel to bedding, pipes, and contact ore bodies are most typical for limestones that are characterized by the anisotropy, high yield to mechanical stress, and high chemical activity.

3. Influence of country rocks on composition of ascending postmagmatic ore-bearing solutions. During assimilation of enclosing rocks magma could acquire a certain amount of ore elements which later became part of postmagmatic mineralizing solutions. It is a more or less established fact that Si, Ca, Mg, Al, Ba, B, and other petrogenic elements, as well as Fe, Mn, and Ti, are assimilated by postmagmatic solutions from the enclosing rocks. The assimilation of typical metallogenetic elements from the country rocks is still little studied and is hypothetical.

The author concludes that the partisans of the lateral-secretional hypothesis, on the one hand, and those supporting the hydrothermal hypothesis, on the other, are generally not taking into account the interrelation of all natural phenomena.

M. N. Godlevsky, Problem of Genesis of the Copper-nickel Sulfide Deposits of the Siberian Platform (Pp. 16–30).

The copper-nickel deposits of the Siberian platform are genetically related to the trap formation. One group of deposits is of complicated genesis. It is mainly of liquation origin and is associated with intrusions of the Noril'sk type. Another group is of hydrothermal origin and is related to intrusions of the Tymersky type. The differentiated intrusions of the Noril'sk region consist of six horizons characterized by the gravitational- and crystallization-fractionation of intrusions.

Magmatic Liquation.—The high concentration of sulfides in intrusions of the Noril'sk type is due to gravitational effect. The main factors contributing to separation of immiscible sulfides in magma are: the concentration of sulfur, composition of the silicate magma (especially the content of Fe, Mg, and Si), and the content of chalcophylic elements in the liquid silicate phase. FeS and Cu_2S possess the capacity of perfect miscibility in liquid state. Nickel sulfide, on the other hand, may form only about 20 percent of the pyrrhotite melt. The maximum of copper content is characteristic of the early stages of hypabyssal liquation, while the amount of nickel remains fairly constant throughout the process. Sterile pyrrhotite appears in the uppermost zones among the products of residual crystallization.

Crystallization of Sulfide Melt.—The near-surface character of Noril'sk type intrusions was characterized by relatively low pressure. Sulfides began to crystallize only after all silicates consolidated. The presence of solid solutions and products of their dissociation indicate the high temperature of liquation ore formation. The first mineral to crystallize is nickeliferous pyrrhotite, which is followed by pentlandite and chalcopyrite. Under conditions of gravitational differentiation the lower parts of sulfide droplets consist of pyrrhotite and the upper parts of chalcopyrite. During filtration differentiation a part of the pyrrhotite is already crystallized; therefore the squeezed-out liquid is enriched in nickel and copper. The bornite-millerite veins are the extreme products of differentiation.

Crystallization of Residual Liquid.—Water and probably other volatile components are present in sulfide liquid. Serpentine, amphibole, chlorite and most commonly biotite, accompanied by the secondary chalcopyrite, form around sulfides in impregnated ores. Nickeliferous pyrite, millerite, and chalcopyrite with microscopic grains of platinum and gold form at lower temperatures instead of pyrrhotite, pentlandite, and chalcopyrite. The evolution of residual melt is illustrated by the physico-chemical diagram of the ternary system Cu_2S-Na_2S-H_2O at pressure of 200 atm.

Formation of Hydrothermal Postmagmatic Ores.—The hydrothermal deposits consist predominantly of pyrrhotite. Solutions from which they were derived probably separated from the sulfide melt formed due to liquation and could also form directly from the silicate melt. Hydrothermal deposits of the Siberian platform are associated with the Tymersky intrusive complex. The presence of chlorine and alkalies in the ore-forming solutions is indicated by the presence of scapolite.

All processes of metallogeny of the Siberian platform are close in time, while those of the shields are characterized by long time intervals between intrusion and formation of massive ores.

V. T. Matveenko, Tungsten Mineralization of the Northeast of the USSR (Pp. 31–48).

The northeastern Mesozoic-Cenozoic metallogenetic province of the Pacific metallogenetic belt is characterized by the endogenetic mineralization of various compositions associated with granitoid intrusions. Besides gold, tin, and lead-zinc mineralization, tungsten is a typical metallogenetic element in Mesozoic folded structures. The concentration of tungsten lessens with decrease of depth of formation of tin deposits. However, in skarns that occur at moderate depth, scheelite forms in considerable accumulations. High temperature of tin and wolframite-quartz formations are absent in skarns. Tungsten deposits and occurrences form six independent formations. The formation of scheelite-bearing skarns and wolframite-silicate formation (tourmaline and chlorite sub-types) are of greatest practical interest. A map of northeastern Siberia indicates belts of established and prospective tungsten-bearing zones surrounding the Kolyma River basin. Details on regional structure, stratigraphy and lithology are included, as well as data on paragenesis of tungsten-bearing minerals, some of which exhibit colloform structure.

V. S. Myasnikov, Some Peculiarities of Titanomagnetite Ore Deposits of the Southern Urals and their Metamorphism Pp. 49–62).

Proterozoic basic rocks of the Southern Urals contain titanium mineralization along a discontinuous 76 km long belt. Regional, contact, and hydrothermal metamorphism altered the rocks and ores in varying degree. Regional metamorphism was of greatest importance, but it was not uniformly developed along the entire belt. The difference in structure and texture and, to some extent, in composition of ores is explained by the degree of alteration caused by the superimposition of later metamorphic processes. The primary ores were represented by titanomagnetite of constant chemical composition. In the southern part of the belt the ores were not altered. The ore pattern due to exsolution remained undisturbed. In the northern area the metamorphism resulted in cumulative crystallization of il-

menite within the grains of titanomagnetite on account of the exsolution product. Later recrystallization of titanomagnetite resulted in the formation of small grains of ilmenite and megnetite. The alteration transformed the titanomagnetite ores to high-grade ilmenite-magnetite ores. Therefore, prospecting for deposits of the latter type has to be conducted in areas where the ore-bearing basic rocks were the subject of intensive regional metamorphism.

M. S. Strakhova, Mineral Composition and Peculiarites of Ore Formation in Ferberite-antimonite Deposits of Gornaya Racha (Pp. 62–73).

The Tertiary tungsten-antimony deposits of Gornaya Racha (Western Georgia) are located along the southern slope of the main Caucasus range and are of a type similar to deposits of Boulder County in Colorado and Barun-Shiveya in the Transbaikal region. The mineralization is associated with faulted and shattered zones in shales of Liassic age. The veins are 0.1 to 1.5 m thick and are related to dacite intrusions. The first stage of mineralization begins with silicification, sericitization, and chloritization of the wall rocks, with fine-grained arsenopyrite and pyrite impregnation. The next stage is represented by ferberite and quartz, mainly in the central part of the mineralized belt. During the last stage of mineralization antimonite and quartz were deposited with some berthierite and hydromica. The appearance of berthierite indicates the reduction of sulfur concentration and increase of iron amount in the residual solution. This deposit has some features of a specific type of epithermal tungsten mineralization.

M. V. Pavlov, M. T. Yanchenko, Some New Data on Magnesian Magnetites (Pp. 74–80).

The investigation of magnesian magnetite from iron deposits associated with trap of the Siberian platform included heating without oxygen up to 500–900° C. It was demonstrated by X-ray and mineragraphy that homogeneous grains of magnesian magnetite, with MgO content ranging from 1 to 14 percent, dissociate into magnesian ferrite and hematite. The formation of hematite is indicated by the first exothermal peak between 350 and 560° C. The size of peak depends on the amount of FeO present. The second peak of unknown character forms at 610–710° C.

B. D. Klagish, Magnetite-carbonate Ores in the Series of Ferruginous Quartzites of the Magnetic Anomaly of Kursk (Pp 81–93).

A new type of magnetite-carbonate ore was discovered in 1954 in Lebedinsky deposit within the 200–300 m thick formation of Precambrian banded ferruginous quartzites. The magnetite-carbonate ore bed is stratigraphically associated with the lower part of the ferruginous formation. The ore bed is 2 to 15 m thick and may be followed 1 to 2 km along the strike. The ore consists of magnesian-ferrous carbonate and magnetite and contains up to 50 percent Fe_2O_3. Minerals of secondary importance are represented by silicates, iron sulfides, and some finely-disseminated graphite. The carbonate belongs to the isomorphic series magnesite-siderite. $CaCO_3$ and $MnCO_3$ are present in small amounts. The author concludes that the ore is the result of metamorphism of a specific facies of sedimentary ferruginous formation.

N. A. Rozanova, Relation of Dikes of Melanocratic Rocks to Gold Mineralization in the Central Deposit (Kuznetsk Alatau) (Pp. 94–100).

The deposit is located in a massif of Caledonian biotite-hornblende granodiorites. The mineralization is represented by a series of veins parallel to the contact of the ore-bearing zone with the beresitized[2] granodiorites. The ore-bearing zones are displaced by transversal melanocratic dikes. The composition of dikes changes along the strike from diabase to microdiorite or to spessartite type. The dikes served as barriers to mineralizing solutions. The hydrothermal alteration of dikes and granodiorites in areas adjacent to the ore-bearing zones belongs to the same stage of mineralization.

G. N. Komarova, Morphologic Features of Cassiterite from the Dzhalinda Deposit in Malyi Khingan (Pp. 101–103).

This Far Eastern deposit belongs to a group of Upper Cretaceous deposits characterized by the so-called wood-tin and which are gentically associated with acid effusives. The colloform cassiterite demonstrates perfect concentric zoning. Another form of colloform cassiterite is represented by the capillary tubes. These microscopic tubes are lined with cassiterite and their central parts are filled with chert. The colloform features of cassiterite are considered as an indication of metacolloidal origin.

Professional Events

E. I. Shatalov reports on the conference on metallogenetic maps which took place in Alma-Ata on December 8–12, 1958 (pp. 109–116). Eight hundred specialists representing 96 scientific and industrial institutions, institutions of higher education, and the administration discussed the problems of development of mineral resources in Kazakhstan, a subdivision of the territory of the Soviet Union into metallogenetic provinces, principles of regional metallogenetic analysis based on the concept of the evolution of geosynclinal zones, metallogenetic maps of platforms and particular regions, and metallogeny of particular ores. The metallogenetic maps are designed to summarize all available information on known types of mineralization and to serve as guides in forecasting the location of prospective ore-bearing areas. The conference recommended the introduction in geological institutes and faculties of a course in metallogeny, as a new branch of earth science.

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DEPARTMENT OF GEOLOGY,
COLUMBIA UNIVERSITY,
Dec. 6, 1960

Tectonic Development of Czechoslovakia. Pp. *262*, 5 folded cross-sections, coloured tectonic map scale 1:1,000,000. Prague (Academy of Sciences), 1960. Price (bound) Kčs 36.50 (£1.10.0 sterling).

As a contribution to the Tectonic Map of the World, a committee of the Czechoslovak Geological Survey has produced this "modest study which we hope will contribute to the strengthening of international co-operation in geological

[2] Beresitization is a type of rock alteration characterized by pyritization of granitic rocks and serves as guide in prospecting for gold.

science, the good tradition of which is based on the works of the International Geological Congress." The "modest study" is quite a formidable compilation of papers by seven authors, presented to elucidate a beautifully printed map which illustrates the historical-tectonic development of Czechoslovakia. The country is built up of two very different tectonic units, the 'Bohemian Massif' of Variscan origin in the west and the 'West Carpathians' of Alpine derivation in the east. The former comprises one of the most complicated tectonic provinces in Europe, and whilst the essays about it are not at all easy reading (what works on tectonics are?), one of the many useful purposes they serve is to illustrate the multiphased history of the granites of Krušné hory (better known to us as the Erzgebirge) with which numerous well-known ore-bodies are associated. It is pleasing to see this Czechoslovak work printed in the English language and marketed to Western geologists at a low cost.

C. F. D.

Geological Survey in 1960. Under direction of V. E. McKelvey. Pp., Part A, 136; Part B, 515. U. S. Geological Survey Prof. Paper 400, Washington, D. C., 1960. Price, $1.00 and $4.25.

The Geological Survey has embarked on a new experiment in the publication of this two-volume professional paper. It represents another major effect to develop suitable means of releasing promptly the essence of new technical findings of both economic and scientific significance. The report is divided into two parts. Part A is a narrative, *Synopsis of Geologic Results*—a summary of important new findings either as yet unpublished or published during fiscal 1960. The individual items consist mostly of a paragraph or so listed under Mineral Resource Investigations, Regional Geology, Geologic Processes and Principles, Analytical and Other Laboratory Techniques, Investigations in Progress, and a list of publications during 1960. It is a very handy reference of what is going on in the Survey and by whom.

Part B, *Short Papers in the Geological Sciences,* consists of 232 short papers mostly one to two pages in length. Some of these are announcements of new discoveries or observations on problems of limited scope that may be published later. Others summarize the conclusions of investigations that have been in progress for some time and which will be published in extended form at a later date. These summaries are arranged under headings of mineral deposits, exploration and mapping, engineering geology, geology of the United States, Alaska, Hawaii, Puerto Rico and Antarctica, paleontology, and other earth sciences.

The public will find much of interest in these two volumes. The arrangement is such that one can pick out readily the subjects of interest to him. Part A can be read in full since the narrative part is only 73 pages in length. It brings home the realization of the scope and products of the survey's work. The long Part B is so arranged and indexed that a geologist can choose the subjects of his particular interest. It also permits one to keep abreast of what is going on in fields other than his own.

If this volume meets approval the Survey will probably try to publish a similar volume annually. We sincerely hope it will.

This volume is confined to the results of the Geologic Division only, but it is tentatively planned to expand volumes to include the work of other Divisions.

We congratulate the Director and Mr. McKelvey for an excellent forward step and a valuable timely contribution to all geologists.

A. M. B.

Methods and Techniques in Geophysics, Volume I. Edited by S. K. Runcorn. Pp. 374. Interstate Publishers, Inc., New York, 1960. Price, $10.00.

The Editor felt that while much literature has appeared on observational data in pure geophysics and theories about the interior of the earth no comparable literature concerning the modern advances in physical techniques has appeared. Thus the purpose of this book.

Thirteen authors have participated—five from England, five from Canada, and three from the United States. Ten papers make up the volume, as follows: Measurement of Temperature Gradient in the Earth by E. C. Bullard; The Measurement of Heat Flow over Land, by A. D. Misener and A. E. Beck; Borehole Surveying, by T. F. Gaskell and P. Threadgold; Measurement of the Geomagnetic Elements, by K. Whitham; Measurements in Palaeomagnetism, by D. W. Collinson and K. M. Creer; The Measurement of Gravity at Sea, by J. C. Harrison; The Detection of Earth Movements, by P. L. Willmore; Earth Currents, by G. D. Garland; Properties of Rocks under High Pressure and Temperature, by D. S. Hughes; Latitude and Longitude, and the Secular Motion of the Pole, by W. Markowitz.

Each paper takes up the instruments involved and how they are utilized, the various methods of measurement, the principles involved, and the results. The coverage is quite complete. The book should prove to be a valuable reference to all theoretical and practicing geophysicists, and to geologists.

Elements of Crystallography and Mineralogy. By F. A. Wade and R. B. Mattox. Pp. 332; figs. 335. Harper & Bros., New York, 1960. Price, $7.50.

A very elementary text presenting over two hundred descriptions and properties of the more common minerals and methods for their identification. The individual chapters take up the concept of matter, crystalline state, classification of crystals, crystal chemistry, physical and chemical properties, descriptive mineralogy, and economic and genetic mineralogy.

With so many good standard texts on the elements of crystallography and mineralogy one wonders why this one is published. Some of the text reads somewhat like an attempt to rephrase parts of Dana's textbook. Also, one notices some carelessness in preparation. For example, on page 80 the right and left quartz crystals are interchanged, and the poor shading of Fig. 4.1. on page 39 makes the lower left rear corner of the cube stand in front of the central diagonal plane. The last two chapters on economic mineralogy and genetic mineralogy are an addition to most textbooks on elementary mineralogy and serve a useful purpose, even though some unfamiliarity with recent trends in the subject is noted.

Geology of the Industrial Rocks and Minerals. By Robert L. Bates. Pp. 441. Harper & Brothers, New York, 1960. Price, $10.00.

The author in his preface points out that most books on the non-metallic minerals and rocks tend to emphasize extraction, preparation, and use, rather than geology, and the role of origin and geologic relations is given minor consideration. Dr. Bates in this book emphasizes occurrence, origin, and geologic interrelations. For this purpose he has devised a geometric classification of which the main headings are: I. Industrial Rocks—igneous, metamorphic, and sedimentary. II. Industrial Minerals—igneous, vein and replacement; metamorphic; sedimentary minerals and sulfur; and minor industrial minerals. This

classification is simple and effective, although not as complete as Bateman's genetic classification of the nonmetallics in his Economic Mineral Deposits. The organization of the book is based upon this classification.

The author has chosen 13 rocks and 20 minerals for discussion arranged according to his classification. Following an introduction and classification, these are taken up in order starting with igneous rocks. The various kinds of industrial rocks are considered, giving their uses, economic factors, properties, occurrence and origin, extraction; and selected descriptions of one or a few typical deposits, and references.

A similar treatment is followed with industrial minerals, although nepheline syenite and negmatites are included under industrial minerals rather than under industrial rocks.

The book is a handy reference, although much more restricted in scope than the classic Industrial Minerals and Rocks published by the American Institute of Mining, Metallurgical, and Petroleum Engineers. It does, however, give somewhat more geology and less of the economic features. It should serve as a useful text for an elementary course.

BOOKS RECEIVED

ROGER L. AMES AND JOHN E. COTTON

Structural Geology Laboratory Manual, 2nd Edit. J. C. LUDLUM and J. M. DENNISON. Pp. 145; figs. 68. Price, $2.95. West Virginia University Bookstore, Morgantown, 1960. *This revised manual has eleven chapters including dip determinations from drill cores and analysis of attitudes of planar and linear structures.*

Les bauxites, leur minéralogie et leur genèse. A translation from Russian. Service d'Information Géologique, Paris, 1960. *A French translation of the 26 chapters (482 pp.) comprising the 1958 Russian symposium on Bauxites (reviewed in* ECONOMIC GEOLOGY, *1959 pp. 957–965, 1325) is now available in whole or in part at the rate of about 0.70 N.F. (about 14 cents) per typescript page.*

Minerals Yearbook, 1959. Vol. I. Metals and Minerals (Except Fuels). Pp. 1271; **Vol. II, Mineral Fuels.** Pp. 483; **Vol. III, Area Reports.** Pp. 1134. U. S. Bureau of Mines, Washington, D. C., 1961.

Imperial College of Science and Technology (University of London) Royal School of Mines Research Report 1957–1960. Pp. 69, figs. 23. *A series of short reports covering research in mining geology, applied geochemistry, oil technology, applied geophysics, extraction, and physical metallurgy, mineral dressing and mining.*

Bulletin Scientifique et Économique du B.R.M.A. No. 6. Pp. 104. Bureau de Recherches Minières de l'Algérie, Birmandreis, 1959. *Eight articles on petrology of volcanics, palynological dating of volcanics and diamond exploration in the Sahara region. In French.*

Table Alphabétique Générale 1950–59 du Bulletin des Séances. Pp. 127. Académie Royale des Sciences d'Outre-Mer, Bruxelles, 1960.

Limestones of Ghana. J. MITCHELL. Pp. 78; pls. 10 (in separate pocket); figs. 6; tbls. 5. Price, 11s. 6d. Ghana Geological Survey Bull. 23, Accra, 1960.

Discussion of limestone deposits is divided into two parts: 1) those with a low magnesium oxide content (suitable for manufacture of Portland cement) and 2) those not suitable for cement.

Annual Report of the Department of Geology and Mining Madhya Pradesh for the Period 1-11-56 to 31-12-57. Pp. 20; tbls. 2. Price, 8 annas. Natural Resources Department, Indore, 1960.

The Geology and Mineral Resources of the Kinta Valley Perak. F. T. INGHAM and E. F. BRADFORD. Pp. 347; pls. 18; figs. 22; tbls. 17. Map, scale 1/5,500,000. Price, $10.00 (Malayan). Geological Survey of the Federation of Malaya District Memoir 9, Ipoh, 1960. *The Kinta Valley is the largest producer of alluvial cassiterite in the world. It is recovered by dredging or by hydraulic and gravelpump opencast mining.*

The New York Academy of Sciences Publication List. Pp. 54. New York, 1960. **The Geology of the Livingstonia Coalfield.** W. G. G. COOPER and F. HABGOOD. Pp. 51; pls. 6; tbls. 5. Map, scale 1/50,000. Price, 10/6. Nyasaland Protectorate Geological Survey Department Bulletin 11, Zomba, 1960. *No reliable estimates of reserves can be given due to extreme lateral variation in coal quality.*

Coal Resources of Ohio. R. A. BRAND and R. M. DELONG. Pp. 245; figs. 22; tbls. 38. Ohio Geological Survey Bull. 58, Columbus, 1960. *Total coal reserves at present are estimated at 46 billion short tons.*

Boletin de la Universidad Nacional de Ingenieria, Vol. 32, No. 4, Peru, 1959. *Five articles on: the Lincoln Tunnel; knowledge of metals; petroleum potential and exploitation in Peru; and the French atomic development.*

Analisi e Preparazione del Minerali. Bibliografia Internazionale Scientifico-Tecnica. Pp. 121. Consiglio Nazionale delle Ricerche, Rome, 1959.

Annual Report of the Geological Survey Department for the period April 1959–March 1960. Pp. 27. Price, Shs. 2/–. Somaliland Geological Survey, Hargeisa, 1960.

An Iron Ore Deposit at Jebel Abu Tulu. A. O. MANSOUR and W. ISKANDER. Pp. 41; figs. 30; tbls. 6; charts 4. Republic of the Sudan Geological Bull. 6, 1960. *This deposit was discovered in 1956.*

Sand—Its Origin, Transportation, Abrasion and Accumulation. H. KUENEN. Pp. 33; pls. 7. The Geological Society of South Africa Alex. L. du Toit Memorial Lectures No. 6, Johannesburg, 1959. *Annexure to Volume LXII, giving text of sixth Lecture.*

The Mineral Resources of the Union of South Africa, 4th Edit. Pp. 622; pls. 23; figs. 15; folders 4. Mineral Map, scale 1/2,000,000; Geologic map, scale 1/4,000,000. Price, £1.13s.3d. Union of South Africa Department of Mines, Pretoria, 1959. *Gold production has accounted for over 77% of the total value of mineral products.*

Notes of the Shearing Resistance of Soft Clays. JUSTUS OSTERMAN. Pp. 22; figs. 13. Price, Sw. Kr. 7.00. Acta Polytechnica Scandinavica, Civil Engineering and Building Construction Series Ci 2, Stockholm, 1960. *A development showing the importance of the value of the Common Quick Testing method. In English.*

Annual Report of the Geological Survey Department 1959. Pt. I. Administrative. Pp. 20. Maps 2, scale 1/125,000. Price, Shs. 3/–. Tanganyika Ministry of Mines and Commerce, Dar es Salaam, 1960.

Aspects of the Geology of Texas: A Symposium. Pp. 117; pls. 6; figs. 66. Price, $2.00. University of Texas Publ. 6017, Austin, 1960. *Contains papers originally presented in Austin in 1958.*

Bibliography and Index of the Geology and Mineral Resources of Washington 1937–1956. W. H. REICHERT. Pp. 721. Price, $2.00. State of Washington Division of Mines and Geology Bull. 46, Olympia, 1960. *Includes references and indexes to all the known published and unpublished papers on mineral resources and geology for the state between 1937–1956.*

Geoloski Glasnik broj 4. Pp. 323. Institute of Geologic Research, Sarajevo, Yugoslavia, 1958. *Eight articles on Paleozoic biostratigraphy, tetrahedrite in sulfide ore, syngenetic iron of nickel deposits, meteorite falls, sulfur springs and tin and molybdenum deposits.*

Soils of the North Central Region of the United States. Pp. 192; figs. 26. Price, $2.00. North Central Regional Publ. 76, Madison, Wisconsin, 1960. *A comprehensive review of soil formation factors, soil groups and associations.*

Stratigraphic Cross Section of Paleozoic Rocks West Texas to Northern Montana. JOHN C. MAHER, Editor. Pp. 18; fig. 1; cross sections 6. American Assoc. Petroleum Geologists, Tulsa, Oklahoma, 1960.

The Oil Producing Industry in Your State (1960). Pp. 92; charts 4. Independent Petroleum Association of America, Tulsa, Oklahoma, 1960.

Energy from Uranium and Coal Reserves. R. D. NININGER, C. I. GARDNER, M. F. SEARL, and D. W. KUHN. Pp. 7; tbls. 9. Price, 50 cents. U. S. Atomic Energy Commission, May, 1960. *Contains a summary of uranium reserves, recoverable coal reserves, and energy from uranium and coal reserves.*

Bureau of Mineral Resources, Geology and Geophysics, Commonwealth of Australia—Melbourne, 1960.

Report 41A. Summary of Oil-Search Activities In Australia and New Guinea to June, 1959. Pp. 92; pls. 11; tbls. 10. *A concise review of the geology, present status of exploration, and prospects of the several basins.*

The Australian Mineral Industry, 1959 Review. Pp. 205; tbls. 289. Price, 20/–. *Contains a general review of the mineral industry and a review of mineral production.*

California Division of Mines—San Francisco, 1960.

Bull. 179. Geologic Reconnaissance of the Northern Coast Ranges and Klamath Mountains, California. W. P. IRWIN. Pp. 80; pl. 1; figs. 16; photos 15. Price, $3.00. *Gold, chromite, mercury, copper, and manganese have been mined in this area.*

Geologic Map of California, Ukiah Sheet. Map, scale 1:250,000. Price, $1.50.

Geological Survey of Canada—Ottawa, 1960–1961.

The Story of The Mountains in Banff National Park. HELEN R. BELYEA. Pp. 42; figs. 37. Price, 50 cents. A well-designed booklet for the layman.

Bull. 62. A Palynological and Geological Study of Pleistocene Deposits in the James Bay Lowlands, Ontario (42 N½). J. TERASMAE and O. L. HUGHES. Pp. 15; figs. 6. Price, 50 cents.

Paper 60-11. Iron and Titanium in the Morin Anorthosite, Quebec. E. R. ROSE. Pp. 12; fig. 1. Price, 50 cents. *The author concludes that disseminated deposits of titaniferous magnetite may be regarded as late magmatic, whereas the ilmenite lodes may be regarded as residual liquid or fluid injections.*

Paper 60-15. Hayesville and McNamee Map-Areas, York, Northumberland, and Carleton Counties, New Brunswick. W. H. Poole. Pp. 10. 2 maps, scale 1:63,360. *Ordovician rocks that are close to granitic bodies in the area appear to be the most likely to be mineralized.*

Paper 60-16. Cretaceous Rocks Between Smoky and Pine Rivers, Rocky Mountain Foothills, Alberta and British Columbia. D. F. Stott. Pp. 20; fig. 1; tbl. 1; 1 map, scale 1:4 miles. Price, 50 cents. *Provides data for the correlation of the known Cretaceous to that of the Central Foothills of Alberta.*

Paper 60-18. Surficial Geology of North-Central District of MacKenzie, Northwest Territories. B. G. Craig. Pp. 8; tbls. 2; Map, scale 1:1,013,760. Price, 50 cents.

Paper 60-19. Virginia Falls and Sibbeston Lake Map-Areas, Northwest Territories 95F and 95G. R. J. W. Douglas and D. K. Norris. Pp. 26; figs. 2; 2 maps, scale, 1"/4 miles. Price, 50 cents. *This mapping in the southwestern part of the Northwest Territories has shown this region to have structural features favorable for oil accumulation.*

Paper 60-21. Beryllium Occurrences in Canada (Preliminary Account). Robert Mulligan. Pp. 40; tbl. 1. Price, 50 cents. *Beryllium occurs in pegmatites, high temperature and pegmatic quartz veins, granite (as disseminations), and skarn deposits.*

Paper 60-25. Ground-Water Resources of the Rural Municipality of Cory (No. 344), Saskatchewan. A. M. Toth. Pp. 6; figs. 2. Price, 50 cents. *Water from surficial sediments is extremely hard; water from sand lenses in the shale bedrock is soft and saline.*

Paper 60-27. Surficial Geology Upton, Quebec. N. R. Gadd. Pp. 4. Map, scale 1:63/360. Price, 50 cents.

Paper 60-28. Surficial Geology of Cornwall Map-Area, Ontario and Quebec. J. Terasmae. Pp. 4. Map, scale 1:63,360. Price, 50 cents. *Gravel pits in this area were opened to provide material for the St. Lawrence Seaway project.*

Mineral Information Bull. MR 44. A Survey of the Uranium Industry in Canada, 1959. J. W. Griffith. Pp. 46; figs. 6; tbls. 6. Price, 50 cents. *Total value of uranium production climbed to $333 million in 1959.*

National Advisory Committee on Research in the Geological Sciences, Tenth Annual Report (1959–60). Pp. 204. Price, 50 cents. *Subcommittee reports divisions of the Survey, reports on research projects, research grants awarded in 1960–61, and current research in geology in Canada.*

Geological Survey of Great Britain—London, 1960.

Summary of Progress of the Geological Survey of Great Britain and the Museum of Practical Geology for the Year 1959. Pp. 76. Price, 5s.

Bull. 16. Pp. 178; pls. 11; figs. 12; tbls. 4. Price £1. *W. Mykura's paper on "The Replacement of Coal by Limestone and the Reddening of Coal Measures in the Ayrshire Coalfield" suggests that reddening is due to oxidation in late Carboniferous—early Permian time; replacement by carbonate (at low temperature) often occurs adjacent to the oxidized portions.*

Geological Survey of India—Calcutta, 1958; 1960.

Records of the Geological Survey of India Vol. 88, Parts 1 and 2. Pp. 465; pls. 6; tbls. 43. Price, 7sh. each part. *Part 1 is a "General Report of the Geo-*

logical Survey for the Year 1953" by M. L. Krishnan. Part 2 includes articles on the mineral production in 1953; ilmenite sands along the Ratmagiri Coast; and Wolfram deposits near Degana, Jodhpur, Rajasthan.

Records of the Geological Survey of India Vol. 88, Pt. 1 (1958). Pp. 356. Price, 7 sh. *This is the general report of the Survey for 1954.*

Indian Minerals, Vol. XIV, Nos. 1 and 2. Pp. 253; pls. 4; figs. 6; tbls. 5. Price, 4s. 11d. each. *In one paper on the "Exploration for Base Metal Ores in India and World Trends" B. C. Roy emphasizes the need for increased exploration for base metals in India since the country is deficient in these metals.*

Geological Survey of Japan—Hisamoto-chō, Kawasaki-shi, 1960.

An Outline of the Geology of Japan. Pp. 32; figs. 6; tbls. 8. Geologic map, scale 1 : 5,000,000. *A brief treatment of the stratigraphy, igneous and metamorphic rocks, and the geologic history of the islands.*

Rept. 186. Geochemical Study of Brine from Yabase Oil Field. K. Motojima, S. Maki, T. Makino and K. Shibata. Pp. 81. *A study of the distribution of chemical components made during first stage of the oil field development. English abstract.*

Explanatory Text of the Geological Map of Japan. Mukawa (Sapporo-54). Shōichi Yamaguchi. Pp. 34; figs. 6. Map, scale 1 : 50,000. *Two anticlinal areas are being explored to determine petroleum potentials. English abstract.*

Explanatory Text of the Geological Map of Japan. Miyazu (Kanazawa-75). O. Hirokawa and K. Kuroda. Pp. 23. Map, scale 1 : 50,000. *The map area is located in the northern part of central Japan and is underlain by Miocene sediments and a Cretaceous granite mass. English abstract.*

Explanatory Text of the Geological Map of Japan. Miyake-Jima (Hachijō-jima-3). Naoki Isshiki. Pp. 83. Map, scale 1 : 50,000. English abstract.

Explanatory Text of the Geological Map of Japan. Yatsuo. (Kanazawa-28). T. Sakamoto and T. Nozawa. Pp. 69. Map, scale 1 : 50,000. *The Yatsuo area in central Japan is underlain by Tertiary sedimentary and volcanic rocks and some metamorphic torrane. English abstract.*

Geologic Map and Explanatory Text of the Isumi District, Joban Coal Field. Y. Kitagawa and T. Tuzuki. English abstract. Geologic maps, scale 1 : 50,000 and 1 : 10,000.

Illinois Geological Survey—Urbana, 1960.

Circ. 302. Lower Pennsylvanian Clay Resources of Knox County, Illinois. W. E. Perham. Pp. 19; fig. 1; tbls. 39. *Most of the clay tested is suitable for structural clay products; the most favorable areas for prospecting are in the southern portion of the country.*

Rept. of Investigations 214. Classification of the Pennsylvanian Strata of Illinois. R. M. Kosanke, J. A. Simon, H. R. Wanless, H. B. Willman. Pp. 84; pl. 1; figs. 4; tbls. 3. *Presentation of a new rock-stratigraphic classification; the three groups recognized are McLeansboro, Kewanee, and McCormick.*

Kansas Geological Survey—Lawrence, 1960.

Bull. 145. Geology and Ground-Water Resources of Gove County, Kansas. W. G. Hodson and K. D. Wahl. Pp. 126; pls. 6; figs. 18; tbls. 11. *Ground water is obtained from the Dakota Formation, Ogallala Formation, and from alluvial deposits.*

Bull. 142, Pt. 4. Occurrence and Bleaching Properties of Some Kansas Montmorillonite Clays. WILLIAM IVES and W. E. HILL, JR. Pp. 37; figs. 4; tbls. 11. *Six deposits of clay ranging in age from Cretaceous to Pliocene age have been tested and found suitable for commercial use.*

Bull. 142, Pt. 5. Petrology of Marine Bank Limestones of Lansing Group (Pennsylvanian), Southeast Kansas. J. W. HARBAUGH. Pp. 45; pls. 8; figs. 19; tbls. 3. *Small scale lithologic features have had a large effect in localizing solution pores in this oil-reservoir rock.*

Oil and Gas Investigations 21. Underground Storage of Natural Gas in Kansas. J. M. JEWETT and E. D. GOEBEL. Pp. 17; figs. 4; tbls. 2. *Fourteen underground storage sites are currently being used and geologic conditions indicate that more reservoirs are available.*

Manitoba Department of Mines and Natural Resources—Winnipeg, 1960.

Publ. 59-1. Potash Deposits, Rock Salt, and Brines in Manitoba. B. B. BANNATYNE. Pp. 30; figs. 8; tbls. 2. *Brine distribution maps show that dissolved salts in the formation brines increase basinward.*

Publ. 59-2. Geology of the Western Oxford Lake-Carghill Island Area. G. S. BARRY. Pp. 37; fig. 1. Maps 2, scale 1:63,360. *Increased exploration since 1956 has located many mineralized shear zones. Sulfides are widespread as disseminations.*

Publ. 59-6. Fauna of the Manitoba Group in Manitoba. HELEN MCCAMMON. Pp. 109; pls. 13; figs. 2; tbls. 4. Price, $1.00.

Montana Bureau of Mines and Geology—Butte, 1960.

Bull. 16. Mines and Mineral Deposits (except Fuels) Jefferson County, Montana. R. N. ROBY, W. C. ACKERMAN, F. B. FULKERSON, and F. A. CROWLEY. Pp. 122; pl. 1; figs. 16; tbls. 35. Price, $1.75. *Ore deposits are related to the Boulder batholith which underlies most of the county.*

Bull. 17. Progress Report on Geologic Investigations in the Kootenai-Flathead Area, Northwest Montana. 2. Southeastern Lincoln County. W. M. JOHNS. Pp. 52; pls. 4; figs. 7. Price, free. *In this area some gold placers have been worked and vermiculite is being mined at one location.*

Bull. 18. Columbium-Rare-Earth Deposits Southern Ravalli County, Montana. F. A. CROWLEY. Pp. 47; figs. 8. Price, free. *Generally the columbium and rare-earth deposits are found in carbonate rocks within amphibolite layers of pre-Beltian gneisses and schists.*

New Zealand Geological Survey—Wellington, 1960.

Bull. n.s. 68. Origin of Ignimbrites of the North Island, New Zealand: A New Petrogenetic Concept. A. STEINER. Pp. 35; figs. 18; tbls. 5. Price, 9s. *The presence of two contrasting glasses—a glassy base and a mesostasis—differing in their refractive index suggest that liquid immiscibility is a fundamental feature of their emplacement.*

Geological Maps, Sheets 2B, Barrier, and 4, Hamilton. Scale, 1:250,000.

North Dakota Geological Survey—Grand Forks, 1960–1961.

Thirty-First Biennial Report. W. M. LAIRD. Pp. 18; tbls. 2.

Oil in North Dakota, First Half of 1960. Pp. 111. Price, $2.00. *These are the official production statistics for the state.*

Northern Rhodesia Geological Survey—Lusaka, 1960.

Rept. 7. The Geology of the Country Between Magoye and Gwembe. Explanation of Degree Sheet 1637, NE. Quarter. A. R. NEWTON. Pp. 30; pls. 4; tbls. 7; Structural map, scale 1:150,000; Geologic map, scale 1:100,000. Price, 10s. *A sequence of schistose rocks in the lower part and carbonate and calc-silicate rocks above.*

Records of the Geological Survey for the Year ending 31st December, 1959. Pp. 79; tbls. 9; pls. 5; maps 6. Price, £1 1s. *A series of six short reports on the regional geology, one on engineering geology and three articles on special problems plus a bibliography of Northern Rhodesia geology.*

Quebec Department of Mines—Quebec, 1960.

Geological Report 95. South Half of McKenzie Township. Abitibi-East Electoral District. Pt. I. Southwest Quarter and North Half of Southeast Quarter. J. R. SMITH. **Pt. II. South Half of Southeast Quarter.** G. ALLARD. Pp. 71. Maps 2, scale 1:12,000. *Quartz veins are generally barren. Sulfides replace sericite-chlorite schist.*

Geological Report 96. Wacouno-Waco Area. Saguenay Electoral District. ROGER-A. BLAIS. Pp. 58; pls. 12; figs. 2. Maps 2, scale 1:63,360. *Minor sulfides occur in veinlets and as disseminations.*

South Dakota Geological Survey—Vermillion, 1960.

Minerals Report 7. The Mineral Industry of South Dakota in 1959. D. H. MULLEN and A. F. AGNEW. Pp. 12. *The value of the state's mineral products increased 17% over the 1958 value.*

The Biennial Report of the State Geologist for Fiscal Years 1958–59 and 1959–60. ALLEN F. AGNEW. Pp. 71.

Geologic maps, scale 1: 62,500, colored, of following quadrangles: Flandreau, Rutland, Gann Valley, Sharps Corner, Little Eagle, Spring Creek, Miscol, Alexandria, Ring Thunder, Patricia, Winner, and Timber Lake.

Tennessee Department of Conservation and Commerce—Nashville, 1960.

Information Circ. 10. The Coal Industry in Tennessee. E. T. LUTHER. Pp. 58; figs. 16; tbls. 5. *The author concludes with reserved optimism for the long range future for the Tennessee coal industry.*

Report of Investigations 11. Pennsylvanian Marine Cyclothems in Tennessee. C. W. WILSON, JR. and R. G. STEARNS. Pp. 1451–1465; figs. 9. (Reprinted from Bull. Geol. Soc. of America, Vol. 71.) *The authors consider that except for coal and adjacent strata the Pottsville sedimentary rocks of Tennessee were deposited in marine water of considerable depth.*

Virginia Division of Mineral Resources—Charlottesville, 1960.

Bull. 76. Geology and Mineral Resources of Rockingham County. W. B. BRENT. Pp. 174; pls. 19; figs. 3; tbls. 10. Geologic sections 18 map, scale 1:62,500. *The area covers a section from the Blue Ridge to the Allegheny Plateau. Detailed regional stratigraphy and structure descriptions are given.*

Virginia Minerals, Vol. 6, No. 3. Unique Fossils from Virginia. H. B. WHITTINGTON Pp. 7; figs. 5. *Brief, general description of Virginia fossils for the layman.*

Western Australia Geological Survey—Perth, 1959–1960.

Report of the Geological Survey Branch for the Year 1958. Pp. 28; pls. 10; figs. 3. *Includes a paper on the newly found (1958) "Goanna Patch" in the East Murchison Gold Field.*

Bull. 114. Miscellaneous Reports for 1957. Pp. 196; pls. 45; fig. 1. *Thirty-seven short reports, most of which deal with economic geology.*

West Virginia Geological Survey—Morgantown, 1960.

Bull. 19. Oil and Gas Report on Kanawha County, West Virginia. O. L. HAUGHT. Pp. 24; figs. 3. Map, scale 1:62,500. *Close drilling in the zones down to the Oriskany has virtually eliminated the possibility of any major discoveries in this section.*

Bull. 20. Water Resources Kanawha County West Virginia. W. L. DOLL, B. M. WILMOTH, JR., and G. W. WHETSTONE. Pp. 189; pls. 4; figs. 29; tbls. 30. *An investigation to bring together the surface, underground and quality aspects of the water resources of the county.*

U. S. Geological Survey—Washington, D. C., 1960–1961.

Water-Supply Paper 1455-A. Floods of May 1955 in Colorado and New Mexico. W. C. VAUDREY. Pp. 68; pls. 4; figs. 12; tbls. 4.

Water-Supply Paper 1459-G. Iron Content of Selected Water and Land Plants. E. T. OSBORN. Pp. 20; pl. 1; figs. 3; tbls. 5. *Plant roots contain a higher proportion of iron than leaves or stems. The iron content of leaves is a function of the chlorophyll present.*

Water-Supply Paper 1460-H. Ground-Water Problems in the Vicinity of Moscow, Latah County, Idaho. P. R. STEVENS. Pp. 32; pl. 1; figs. 8; tbls. 2. *An excess of discharge over recharge of the artesian aquifer suggests that a critical ground-water shortage will occur in the Moscow basin in about a decade.*

Water-Supply Paper 1464. Geology, Water Resources and Usable Ground-Water Storage Capacity of Part of Solano County, California. H. G. THOMASSON, JR., F. H. OLMSTED, and E. F. LEROUX. Pp. 693; pls. 23; figs. 30; tbls. 53. *A report on the important current water supply of the land area between Sacramento and San Francisco.*

Water-Supply Paper 1480. Evaporation Control Research, 1955–58. R. R. CRUSE and G. E. HARBECK, JR. Pp. 45; pl. 1; figs. 14; tbls. 3. *Of the one hundred fifty-two compounds tested as potential evaporation retardants, the homologous straight-chain fatty alkanols are considered to be most effective and safe. Many important aspects of the retardants have yet to be tested.*

Water-Supply Paper 1482. Geology and Ground-Water Resources of the Gallatin Valley, Gallatin County, Montana. O. M. HACKETT, F. N. VISHER, R. G. MCMURTRY, and W. L. STEINHILBER. Pp. 282; pls. 11; figs. 40; tbls. 36. Map, scale 1:63,360. *The study shows that a considerable increase of withdrawal of ground water could be made without reducing the amount in storage.*

Water-Supply Paper 1494. Geology and Ground-Water Resources of the Matanuska Valley Agricultural Area, Alaska. F. W. TURNER. Pp. 116; pls. 3; figs. 8; tbls. 5. *Till in this region is relatively impermeable. Most wells are tap glacial outwash deposits.*

Water-Supply Paper 1495. Geology and Ground Water in Napa and Sonoma Valleys, Napa and Sonoma Counties, California. FRED KUNKEL and J. E. UPSON. Pp. 252; pls. 5; figs. 7; tbls. 22. *Most water is pumped from alluvium filling the two valleys and from the Sonoma volcanics.*

Water-Supply Paper 1536-A. Borehole Geophysical Methods for Analyzing Specific Capacity of Multiaquifer Wells. G. D. BENNETT and E. P. PATTEN, JR. Pp. 25; figs. 8; tbls. 2. *Conventional well-logging techniques combined with measurements of flow velocity are used to determine discharge-downdraw characteristics.*

Water-Supply Paper 1540-A. Residue Method for Common Minor Elements. JOSEPH HAFFTY. Pp. 9; fig. 1; tbls. 3. Price, 15 cents. *The excitation of the water residue using a d-c arc provides a method for the detection of elements present in low concentrations.*

Water-Supply Paper 1541-A. General Introduction and Hydrologic Definitions. Manual of Hydrology: Pt. 1. General Surface-Water Techniques. W. B. LANGBEIN and K. T. ISERI. Pp. 29. Price, 25 cents.

Water-Supply Paper 1541-B. Double-Mass Curves. Manual of Hydrology: Pt. 1. General Surface-Water Techniques. Pp. 31–66; figs. 8; tbls. 12. *Discussion of double-mass curve method in checking consistency of data.*

Water-Supply Paper 1541-C. Graphical Correlation of Gaging-Station Records. Manual of Hydrology: Pt. 1. General Surface-Water Techniques. J. K. SEARCY. Pp. 67–100; pl. 1; figs. 9–14; tbls. 13. *The graphical correlation method as described in a step-by-step procedure with an illustrative problem of simple correlation.*

Water-Supply Paper 1543-A. Flood-Frequency Analyses. Manual of Hydrology: Pt. 3. Flood Flow Techniques. TATE DALRYMPLE. Pp. 80; figs. 30. *Methods and practices employed by the Geological Survey are described.*

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Vol. 56, 1961, pp. 463–464

SOCIETY OF ECONOMIC GEOLOGISTS INCORPORATED

WALDEMAR LINDGREN CITATION AWARDS FOR EXCELLENCE IN RESEARCH

The Council of the Society of Economic Geologists has approved the presentation annually of up to three *Waldemar Lindgren Citation Awards for Excellence in Research*. These Awards are named in honor of the late Waldemar Lindgren, distinguished economic geologist, author, teacher, one of the founders of the Society and of the journal, Economic Geology.

Each Award shall consist of an appropriately inscribed Citation and $100 in cash. They will be conferred upon *"geologists whose research as college or university students result in papers of high merit on a subject judged important to economic geology."*

The selection of the recipients will be based on the adjudged merit of manuscripts of research papers prepared by student authors and submitted to the Society for consideration. The manuscripts must be prepared with content, style, and length suitable for publication in Economic Geology, and each manuscript must be accompanied by a letter of transmittal by the author and a letter of commendation from his research advisor. Three copies of the manuscript are required.

Any student who is, or who has been within the calendar year in which the paper is submitted, a candidate for a degree in any recognized college or university is eligible to enter the competition.

The papers will be adjudged by a committee, to be known as the Lindgren Citation Awards Committee, drawn from the membership of the SEG Research Committee and appointed annually by the President of the Society.

The first of the Waldemar Lindgren Citation Awards will be made in Society Year 1962. To qualify for consideration for the 1962 Awards, manuscripts must be in the hands of the Secretary of the Society on or before November 1, 1961. The winners will be announced following the meeting of the Council in February 1962, and the formal presentation of the Awards will be made by the President at an appropriate occasion during the 1962 Fall Meeting of the Society.

Changes in the By-Laws

At the annual meeting of the Council of the Society of Economic Geologists, held in Denver, Colorado, October 30, 1960, the Council approved the following changes in the By-Laws:

a. Article I, Section 2, Dues. First sentence which reads

> "The annual dues shall be seven dollars ($7.00) and entitle a member to receive the official bulletin of the Society for one year."

was changed to read

> "Beginning with calendar year 1962, the annual dues shall be ten dollars ($10.00) and entitle a member to receive the official bulletin of the Society for one year."

b. Article III, Section 1. Nomination and Election of Officers and Councilors. Sentence two which reads

> "The Committee shall nominate one candidate for each office to be filled and submit its nominations to the Secretary prior to June 1 of the following Society Year."

was changed to read

> "The Committee shall nominate one candidate for each office to be filled and submit its nominations to the Secretary prior to May 1 of the following Society Year."

The Council also announces the election of Eugene N. Cameron, Professor of Geology, University of Wisconsin, to the Office of Secretary of the Society to succeed Harold M. Bannerman, who, on April 1, became Vice President-Elect.

Dr. Cameron was born in Atlanta, Georgia. He is a graduate (B.S., 1932) of New York University and of Columbia (A.M., 1934; Ph.D., 1939). He taught geology at Columbia University from 1936 to 1942. During this period, he also did field and laboratory research in mineralogy, petrology, and economic geology, and, in 1941–1942, did mapping in Connecticut for the Connecticut Geological and Natural History Survey. In 1942 he joined the U. S. Geological Survey to engage in strategic mineral studies, particularly in the study and evaluation of pegmatite and other non-metallic mineral deposits. In 1947 he was appointed Associate Professor of Geology at the University of Wisconsin, where he has taught courses in economic geology, mineralography, and mineral economics. He became full Professor in 1950 and served as Chairman of the Department from 1955–1960.

At the University of Wisconsin he has been an active participant in research programs. He has also engaged in consulting practice in economic geology involving detailed studies, exploration, and evaluation of mineral deposits in various parts of the United States, Canada, Africa, and South America, and he has served as Chairman of two panels set up under the aegis of the Materials Advisory Board to make a special study of the resources of beryllium and of chromium. He was elected to membership in the Society of Economic Geologists in 1947. He is also a member of the American Institute of Mining and Metallurgical Engineers and of the Geological Society of South Africa; a fellow of the Geological Society of America and of the Mineralogical Society of America.

His many publications cover pegmatites, beryllium, graphite, chromium, manganese oxides, measuring the optical properties of ore minerals, and other subjects.

Dr. Cameron will take over as Secretary of the Society on April 1. His address is: Eugene N. Cameron, Science Hall, University of Wisconsin, Madison 6, Wisconsin.

HAROLD M. BANNERMAN,
Secretary

Economic Geology
Vol. 56, 1961, pp. 465–466

SCIENTIFIC NOTES AND NEWS

SYMPOSIUM ON PROBLEMS OF THE ORIGIN OF POSTMAGMATIC ORE DEPOSITION, WITH SPECIAL REFERENCE TO THE GEOCHEMISTRY OF ORE VEINS

In 1963 a symposium of the above title will be held in Praha, Czechoslovakia to discuss some of the important questions concerning postmagmatic ore deposition. The following questions have been selected for discussion:

1. The origin of primary zoning in ore veins, ore deposits and larger units. Discussion of the following questions will be especially welcomed:
   a) Criteria proving polyascendent * "pulsation" zoning; Causes of the polyascendent origin of hydrothermal deposits.
   b) Criteria proving monoascendent origin and monoascendent zoning.* Criteria proving that different minerals in ore veins were deposited from the same solution, or from the uninterruptedly ascending solution.
   c) Evolution of chemical composition of ore-bearing solutions dependent on the same source.
   d) Other contributions on questions of zoning.
2. Criteria solving the manner of the transport of metals in ore-bearing solutions and comments on the existing views.
3. Reasons for or against the distinguishing of a pneumatolytic phase in the classification of postmagmatic processes.
4. Criteria for the recognition of metacrysts of minerals.
5. Role of selective replacement in hypogene ore deposition.

* See Econ. Geology, vol. 52, pp. 316–319, 1957.

Contributions in one of the Congress languages dealing separately with the individual questions, each of which not to exceed five typewritten pages are welcomed. The number of illustrations should not exceed two pages. Manuscripts ready for print should reach the General Secretary of the Symposium M. Stemprok (Geological Survey of Czechoslovakia, Malostranské nám. 19, Praha 1, Czechoslovakia) before December 15, 1961.

The contributions received will be published as a separate volume available several months before the symposium takes place.

J. Kutina,
Faculty of Natural Sciences,
Charles University,
Praha

and

M. Vaněček,
Geological Survey
of Czechoslovakia,
Praha

Norman Dennis Newell has been named the recipient of the Mary Clark Thompson Medal of the National Academy of Sciences. Dr. Newell is chairman of the Department of Fossil Invertebrates at the American Museum of Natural

History in New York and a professor of Geology at Columbia University. The award will be made during the Academy's annual meeting on April 24 in recognition of his outstanding contributions in the field of paleontology and geology, particularly concerning the ecology of modern and ancient calcareous reefs.

Arizona State University, Tempe, Arizona, marked the acquisition of a large part of the Nininger Collection of meteorites with the help of a Foundation grant for $240,000, by holding a national symposium on meteorites on March 10.

Lamont Geological Observatory, Columbia University's research facility, will add two new buildings with more than 45,000 square feet of laboratory and office space to its establishment at Palisades, N. Y.

LEWIS G. WEEKS, former chief geologist of the Standard Oil Company of New Jersey, will teach a special seminar at Columbia University for advanced graduate students in geology, to be given in the 1960–61 Spring Term and will deal with fundamentals of petroleum Geology. Special attention will be given to principles of petroleum exploration, industrial management, and world petroleum resources.

DONALD H. MCLAUGHLIN has resigned as President of Homestake Mining Co. to become Chairman of the Board. He is succeeded as president by JOHN K. GUSTAFSON.

KENNETH WILSON, formerly Exploration Geologist for American Smelting and Refining Company, has resigned to open consulting offices in San Francisco at 400 Montgomery Street.

CLARENCE L. MOODY, consultant, Houston, has been chosen to receive the Sidney Powers Memorial Medal, highest honor in petroleum geology. He is the 14th recipient of this award, established in 1943 and made in recognition of distinguished and outstanding contributions to, and achievements in petroleum geology. Presentation of the gold medal and scroll will be made on April 25, 1961, at the 46th annual meeting of the Association in Denver, Colorado.

W. T. IRVINE has been appointed chief mines geologist, and R. G. McEachern has been appointed chief exploration geologist of the Consolidated Mining and Smelting Co.

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Facilities in the Mineralogical Section include X-Ray diffraction equipment, projection microscope and infrasizing and superpanning equipment as well as the usual microscopes, photographic facilities and sample preparation equipment. Analytical services are available.

Applicants for the post of Mineralogist should have had some experience in determinative mineralogy and in petrology. The Senior Mineralogist, who would report directly to the Assistant Superintendent of the Division, should have sound experience in the above fields and the ability to co-ordinate and supervise the work of a team of three mineralogists. He would also be required to liaise with geologists and research and plant personnel on mineralogical problems. A knowledge of mineral concentration techniques would be an advantage.

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Replies, stating age, marital status, qualifications, experience record, and availability, together with names of two referees, and a recent photograph, should be addressed by airmail to:—

The Secretaries,
P.O. Box 172,
Kitwe,
Northern Rhodesia

Imperial College of Science & Technology. Research Studentships in Geochemical Prospecting. Applications are invited from Geology Graduates for Research Studentships in applied Geochemistry (£600–£800 p.a. for two years) starting 1st Oct. 1961. Successful applicants will carry out field work overseas during not more than two terms. Apply Dr. Webb, Geology Dept., Imperial College, London, S.W.7. before 1st June.

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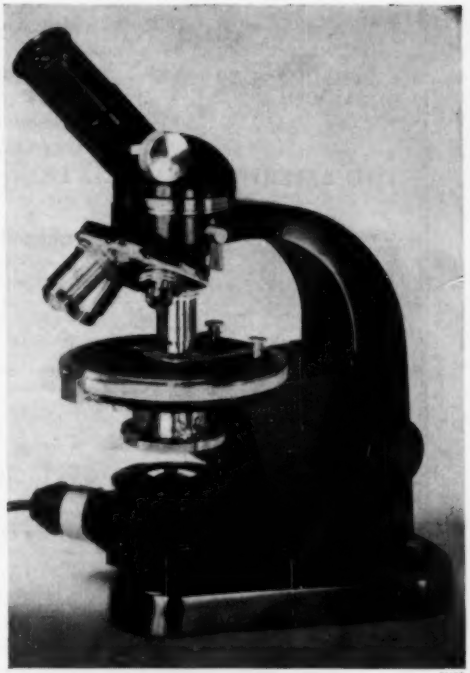

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